INTERNATIONAL GEOGRAPHICAL UNION

EUROPEAN REGIONAL CONFERENCE

SYMPOSIUM ON KARST-MORPHOGENESIS

Papers

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C O N T E N T S

A DETAILED EXPOSITION OF THE STUDY TOURS

1. The Mountains of Buda

The mountains of Buda lie in the neighbourhood of Budapest, on the right bank of the Danube. Considering their development they are block-mountains of ruptured structure. The main bulk of the mountains is built up by dachstein limestone from the upper Triassic and Triassic main-dolomite, situated in the subjacent level. The lines of break creating the mountains are penetrative and from the tertiary period on they made way for the hydrothermas, breaking out from the depth of the Earth. By means of their favourable petrographic and tectonic nature, the mountains of Buda developed one of the world's biggest and in phenomena richest hydrothermal karsts. Among these phenomena the most outstanding are the tufa sediments, deposited from hot water the hydrothermal metamorphisms as well as the caves, come into being by way of hydrothermal corrosion.

The morning's program comprises the inspection of the tufa cave of Várhegy and that the recent hydrothermal karst-phenomena of Gellért hill. Buda's Várhegy is essentially the tufa sediment of thermal springs from the Pleistocene epoch and this mountain is full of caves.

The caves originally came into being by way of natural dissolutinn, but later on they were enlarged artificially and presumably they served as shelters of the inhabitants for centuries. There survived many archeological relies of the historical past in the caves and this huge "network of caves" served as shelters during the second world-war. The Hungarian Company of Speleologists established a cave-museum in Várhegy /Castle Hill/. Some parts of the cave are open to foreign tourist traffic as well.

The afternoon program includes inspection of the cave of Pálvölgy the dolomite caverns of the White Hills in Pilisvörösvár as well as the inspection of the hydrothermal pulverized dolomite-karst.

The cave of Pálvölgy came into being along several tectonic fissures, crossing one another as a result of the solvent effect of the thermal waters, in nummulinal limestone of the eocen epoch. The total length of its galleries is about 620 miles. It is the specific feature of the cave, that it lacks the large hall-like chambers, instead it consists of a network of some high but narrow as well as broad and flat passages. Its biggest room is the chamber named "Theatre-hall".

This cave system was discovered while quarrying, in 1904. In the year 1927 it was opened to tourists too. The cave, built in with concrete pavements and steps, can be inspected comfortably in day dress.

In the immediate neighbourhood of the cave of Pálvölgy some other caves can be found, such as the cave of Mátyás-hill, that of Ferenc-hill, and Szemlő-hill and farther the cave of Solymár. All of them came into being by the effect of tectonics and thermal waters. Especially in the cave of Ferenc-hill there are many originally hot-watered aragonites, while in the above-mentioned cave and in that of the cave of Solymár also some hydrothermal gypsum-sediment can be found.

The hydrothermal dolomite-karst in the neighbourhood of Pilisvörösvár is probably the most characteristic area of the special metamorphisms come into being by the effect of hot springs. From the water of the hot springs of the late Tertiary anhydrite and aragonite have been deposited into the pores of the crystalline structured dolomite. Later on - as soon as the heat effect ceased - these minerals, by way of swelling and expansion, became gypsum and calcite. This process of recrystallization, with the help of the rock texture - loosening activity of the acidic solution of the hydrothermas resulted in dolomite-pulverization of large extension both on the surface and in the depth. In the place of the lifted subsurface degraded dolomite there remained caves illustrative of the subsurface direction of trends of the fissure-systems carrying hydrothermas.

2. Fossilic Karsts from the Cretaceous Period

The purpose of the all-day excursion by bus in the studying of those fossilic karstsurfaces, which came into being as the result of certain tropical climatic effects, in different places of the Transdanubian Hills, at the time of the geological cretaceous, and which have been protected by the deposited bauxite-levels from later denudation.

Leaving Budapest the first bigger settlement on our way is Érd. The name of the settlement is already mentioned in 13th century chronicles. There is a fine minaret deriving from the time of the Turkish occupation. /In Hungary there are only three minarets, the other two are in Eger and Pécs./ In the fifth century a great battle took place between the Western Goths and the Huns in the surroundings of Érd. The neighbouring mounds cover the bones of some 335000 warriors. /E.g. Százhalombatta, which is a settlement recently become the centre of the Hungarian oil industry and oil refinery./

The next important settlement is Martonvásár, where the Agricultural Research Institute of the Hungarian Academy of Sciences is to be found. Ludwig von Beethoven spent quite a long time in the park of Martonvásár, as guest of the Brunswick family. In the park of the castle he got inspiration for many of his works. For instance he dedicated his sonata in F minor /Appassionata/ to one of the Brunswicks. There lived the "immortal sweetheart" as well, to whom many of Beethoven's works are dedicated. In the park, in front of the composer's statue, festival concerts are given every year and in the castle built in 1773 there is a Beethoven museum.

Not much later we can catch sight of Lake Velence called Budapest's bath for fun. The territory of the lake is 26 km^2. About one third of this is covered with reeds. The average depth of the water is only about 60 inch. On the northern shore of the lake can be found the strongly eroded Velence Hill.

In the Western part of the lake of Velence - the water of which reaches a temperature of 20-25^o C in summer - there is a valuable reserve of birds, where even the prince of the avifauna, the Egretta alba can be found.

In a short time we arrive at Székesfehérvár. Thousand years ago this town was the capital of the country. At that time her chief merit was the huge moor, making the town unapproachable from all sides. The original name of the town was ALBA CIVITAS appearing first in the deed of foundation of the nearby bishopric of Veszprém. Later on it was written as ALBA REGIA. Székesfehérvár was most prosperous during the 11th and 12th centuries. Later on it was occupied by the Turks for some 150 years. At the time of the second world war out of her 7000 flats 6000 were destroyed. The main square of the town in the Square of Liberty; in its immediate vicinity there are several mediacval houses. Here is the Bishop's Palace behind it is the famous garden with ancient ruins, which is really an open-air museum, consisting of the remaining ruins of the sometime Royal Basilica.

The Town Museum bearing the name of King Stephen must be mentioned on account of its material representing the local history as well as an account of its exhibitions, demonstrating the fauna and fishing of Lake Velence.

Our further journey leads through the one-time moor, called Sárrét, then from the Veszprém highroad we turn off to the right and reach one of the largest bauxite-areas of the country, the neighbourhood of Iszkaszentgyörgy. Crossing the tectonic depression of the Móri ditch, we soon reach the centre of the place of occurence of bauxite in the Vértes mountains. The name of this place is Gánt.

The surface-mining of the bauxite carried on in the afore mentioned regions, made it possible to study quite a series of tropic karstic micro- and macro forms developed at the time of the Cretaceous Period. In connection with this it must be known that the essentially mesozoic, carbonic central mass of the Hungarian Central Chain of Mountains are lined in the South by a varistid substratum consisting of crystalline shale. This substratum was quite high till the second half of the Mesozoic. Its detritus was washed away by water in the direction of West and North across the carbonic rock surface, constituting today the central mass of the mountains. These /bauxit/ caterite clay minerals of bauxite content filled in the karstic surface formation. Elemér Vadász and György Bárdos carried out essential investigations in connection with the problems of bauxite-formation. They discovered that the biggest layers of Al_2O_3 content run in NE-SW direction in the Hungarian. Central Chain of Mountains. According to their investigations, the primary sediments, accumulated in the karstic dolinas became bauxite on the spot. Consequently the bauxite is not a formation flushed from afar but a clay bearing sediment which was transformed into bauxite by the tropical climate and the karstic holes of the carbonic rocks with the help of the motion of the karst-waters. Bauxites of better quality can always be found at the dolomitic bottom of the rocks; that is also a fact proving the role of the post-bauxite formation. It is interesting to mention that in Gánt a great quantity of Osmudacea fern has been found in the bauxite, indicating definitely a tropical warm, humid climate.

In Iszkaszentgyörgy the karst surface lying under the bauxite can best be studied in the surroundings of the open mining, called Kincses. There are broad, flatted cones and bluff blocks to be seen here. On the side of the blocks cave water courses can be recognised in many places. As in this area the rock material is mainly dolomitic, the solution forms are richly varied.

The occurrence in Gánt, belonging to the ancient karst of the Vértes mountains, attracts the attention with its tower-like conical karst rising from the bauxite. In the neighbourhood of Gánt Bagolyhegy theses cones are 30 m high. At the same time between the cones there are bluff and deep rows of dolina to be found. Here the material of the rock is dolomite, the surface of which shows roundish forms everywhere.

In Hungary we know tropical karstic forms of the same character in the Villányi Mountains which are to be found in Southern Transdanubia. These mountains are also covered with bauxite layers.

3. Study-Tour in the Bükk Mountains

On the first day of the twoday study tour, leaving Capital, we reach Gödöllő, famous for her agricultural academy, then we visit a little town, called Hatvan. Along many kilometres our way leads through melon and tomato fields, then in the neighbourhood of Gyöngyös we see hills planted with vines. Gyöngyös, lying at the foot of the Mátra mountains, is the centre of the wine-production of the region. Leaving the Mátra mountains of vulcanic origin we soon come to Eger. It lies already under the Bükk mountains.

The chief sight of the town is the Castle, which was besieged by 150 000 strong Turkish Army for about two months - but without success. The heroism of the women of Eger took part in the defence of the Castle became famous all over Europe. Inside the Castle there are the famed system of casemates as well as the bishop's palace which today is a museum.

There is a fine minaret still remaining from the time of the Turkish occupation. The iron doors of the baroque building of the country council were made by Henry Fasola.

In the town there is a karst-spring with abundant hot water; for centuries it has been used for medical treatment. The region of Eger is a famous wine producing country; its most famous wines are called "Bikavér" and "Egri medoc". Besides the above mentioned Castle and minaret there is the Teacher-training School and the Cathedral to be seen. The first was built in 1765 and the latter in 1831. On the uppermost floor of the school a huge periscope is to be found. It was made by Miksa Hell. /The other specimen is in Edinburgh./

Leaving Eger we soon reach the narrow <u>rock-canyon</u> in <u>Felsőtárkány</u> and passing through this we enter the karstic territory of the Bükk mountains. From the winding roads in the mountain-side we can enjoy a very beautiful scenery. In the neighbourhood of <u>Répáshuta</u> we reach the sink-hole of <u>Pénzpatak</u> about 600 m from the highway. When ppening it in 1953 László Jakucs and his co-workers discovered a sump-cave of about 150 m deep and 1 km long. The valley of the sump is a characteristic specimen of batükaptura. The terraced basin of the spring is continued in a higher level, as a dry, inactive river valley.

From here we climb up to the Bükk-plateau, which 700-800 meters high on the average. It is a typical karstic territory of relatively flat surface, with lots of dolines. In the majority of cases the dolines are situated in long series in the axis of the sometime erosive valley.

At one point of the plateau, in the neighbourhood of Hosszubérc, the microclimatic research station of Szeged University can be found. With the direction of Professor Wagner this station carries on investigations relating to the study of the microclimate of forests and fields. They study the microclimate of the dolinas with special care, these being especially suitable for comparing different climates within short distances. The research station studies how the cold air lakes in the dolinas develop.

Our next station is at the Palace Hotel of Lillafüred on the shore of Lake Hámor. This Hotel has been built on the huge travertine hill deposited by the waterfall of the Szinva brook. In the thick travertine sediments the sometime waterfalls surrounded different caves. These were connected, thus forming the biggest travertine cave of primitive genetics in Europe. The calcified pine-trees and moss of the Pleistocene Period can still be seen in the cave.

In other caves in the region of Lillafüred palaeolithical prehistoric man used to live. Especially the excavation of the Szeleta, Büdöspest and Otto Hermann caves has brought to the surface many valuable chipped flint implements.

Leaving Lillafüred we go on travelling past the ironworks of Diósgyőr and soon we come to the second biggest town of our country, Miskolc.

After Miskolc we move on in the basin of the Sajó towards the North-West. We reach Sajószentpéter, which is famous for its glass factory, then we reach an important centre of the Hungarian plastics and fertilizer industry. This town is Kazincbarcika. Soon we arrive at the Aggtelek-mountains, which is the most aotable karstic territory in Hungary.

4. Study-Tour on the Aggtelek-Jósvafő Karst

The Aggtelek karst is a karst-plateau, consisting of Triassic limestone, between the villages Aggtelek and Jósvafő. The limestone travertine lying in East-West direction is bordered in the South by a relief covered with gravelled layers. This gravelled and clayey district is the watershed area of numerous intermittent superficial water-courses. But since the general sloping of the surface runs in the direction of the limestone-range, the watercourses become blocked, then they get swallowed at the edge of the bordering limestone-karst and the waters go on flowing in underground canyons and caves in northern direction till the local base level, which is in the deep spring-valley of Jósvafő.
This special geological, geomorphological and hydrological structure has developed one of Europe's biggest cave centre. Here, within a small area, there is a series of cave systems, among which there are still unexplored ones.

Here is to be found the so called "Baradla" stalactite cave, forming the same genetical system with the Czechoslovakian Domica-cave. Its length is about 22 km. The second biggest cave of the country is "Peace" /Béke/ Stalactite Cave, discovered by László Jakucs in 1952. Its length is nearly

10 km. No connection has yet been found between the two caves, though Peace Stalactite Cave approaches Baradla Cave in some places as near as 600-700 meters. In the neighbourhood - near to the village of Égerszög - a smaller cave of some 3 km length has recently been discovered as a result of the significant exploring-research of the last decades. There are some other important caves here, such as Imre Vass Cave and Kossuth Cave, each 1 km long. Near to Imre Vass cave functions the Karst Research Station of the Institute of Scientifical Management of Watersupplies. The workers of the Institute systematically search the numerous phenomena of the cave and those of the surrounding karstic area.

First we go for a walk in the Aggtelek part of Baradla Cave. /This part of the cave can be visited in day-dress and shoes./ Through the bottom of the large wall rocks of the sometime sump we get to a cave-system consisting of huge rock cavities. The sooting which thickly covers the ground and walls is the consequence partly of visits with torches in the last centuries and partly of the fire laid by prehistoric man. In the course of our tour we reach the following places: Csontház, Rókabarlang, Fekete terem, Hangversenyterem, Táncterem, Tigristeremand Oszlopok Csarnoka. /Charnel-house, Fox-cave, Black-Hall, Concert Hall, Dancing Hall, Tiger Hall, Hall of Colums./ Considering that the cave is a storied system and below the visited level there is a so-called lover cave, we do not sec too much running water in the course of our tour at low water period. But in rainy weather when the lower cave has already been filled with water the cave-springs become swollen at this level too. At such times the Acheron and the Styx along with a roaring noise under the vaulted roofs of the galleries.

There is a biological station in the cave, called Rókaág which is the centre of research of the characteristic fauna of this place.

We go on in the direction of the Vöröstó entrance of the cave. Our way leads through corrosive dolinas, 100-200 meters in diameter. Going down the steps of this entrance we take a two hour underground walk in the Jósvafő parts of the cave system. In this part of the cave we can study the erosive ativity of the watercourse as well as the underground terraces of the springs. We come to the highest stalagmite of the cave /25 meter/ and its largest chambers /its name is Óriásterem /Giant Chamber/; it is 200 meters long, 64 meters wide and 40 meters high/, then we come again to the surface through the artificially cut entrance, near to the Tengerszem Hotel.

One of the entrances of Peace Cave is also in the neighbourhood of the Tengerszem Hotel: this cave has not been opened yet for tourism. But for utilizing the excellent asthmatherapic qualities of the cave air in some of its chambers a natural climate-sanatorium has been established where the patients have breathing cures for 4-5 hours a day in turns of two or three weaks. The very favourable results are similar to that of the Klutert-Höhle. As for the cause of the curative effect such facts can be mentioned as the great and uniform vapour-content of the cave's air, its being absolute free from dust and allergens, as well as the fact that the aerosol-containing calcium exerts a certain antiphlogistic effect through the pulverization of the water dropping down from high.

The surface terraces of the Jósvafő-valley are fairly parallel with the floors of the caves. Most of the floors are to be found in Imre Vass cave. /There are 5 of them here./ Of course numerous further investigations are needed for an exact explanation of the genetics of the caves and of the surface karst-phenomena.

D. B a l á z s

RELIEF TYPES OF TROPICAL KARST AREAS

The difference in the phenomena of tropical karst landforms caused the geographers to give them peculiar names. Mostly the names given by German geographers /Lehmann, H., Wissmann, H./ are used: "Kegelkarst" and "Turmkarst" and their English /cone karst and tower karst/ and French /karst à pitons, karst à tourelles etc./ versions. In the course of study of the Caribbean Archipelago a number of new concepts were adapted by the scientific literature /cockpit karst, "mogote karst, haystock karst, morne karst, etc/ causing many misunderstandings.

In our view the concepts of "Kegelkarst" and "Turmskarst" are not suited for the determination of the type of tropical karst regions. The "Kegel" /cone/ and "Turm" /tower/ shapes often occur within the same karst region, in another's vicinity. The cones may develop in time into towers and the towers into cones. It is extremely difficult to determine for instance ot the region shown in Figure 1, wether it is of Turmkarst or Kegelkarst type, since both formations are present in compact and isolated full forms.

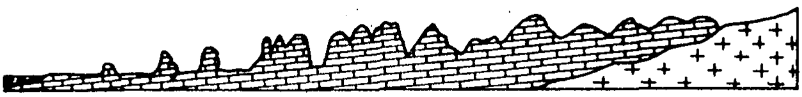

FIG. 1.

It seems more reasonable to consider a continuous karst region as an independent morphogenetical unit and to attempt to typity it on the basis of the complex geological development of the region. However this task is made more difficult by the circumstance that each tropical karst region is the result of individual development and many factors contribute to the trend of development /lithologic, tectonic, orographical and conditions, etc./. The subjects of our investigations are solely the plain- and plateau - like, thus approximately horizontal, karst regions and they do not extend over karst regions of high mountainous or specific character.

Similarly to the volcano experts who marked out certain characteristic volcanos as head-types /i.e. Stromboli type, Vesuvio type, etc./ it is possible to select characteristic types of tropical karst, though the steps of development follow a substantially slower course than in volcano morphology. The selection of tropical morpho-genetical karst types is made possible by the peculiar full forms characteristic of each karst region, forming about 70-80 % of the karst region in question.

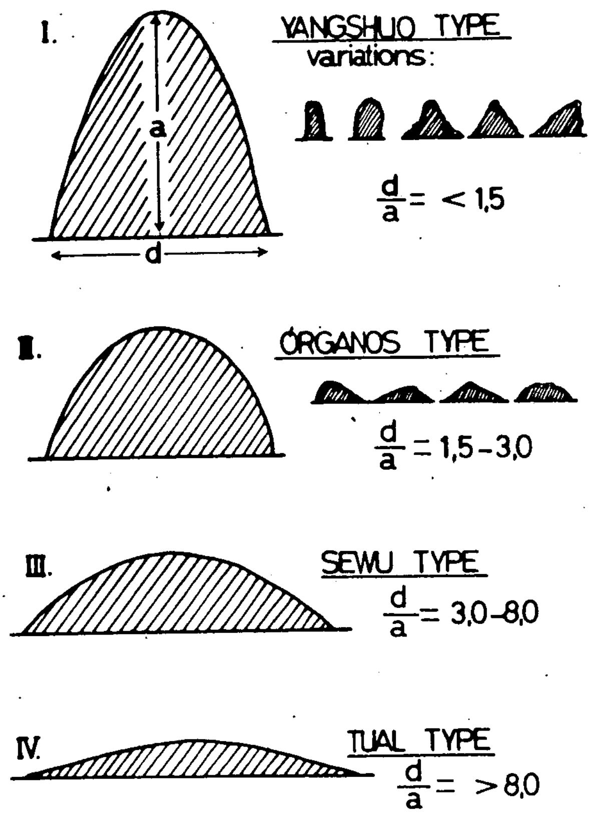

FIG. 2.

Basen on the development of the full forms characteristic of the tropical plateau karstlands <u>four head types</u> could be established. The schematic diagram of these is illustrated <u>in Figure 2</u>. The quotient of the diameter /d/ measured at the base of the hills and their altitude /a/ is the main characteristic of each type /morpho-genetical index, herafter: m.g.i./.

For the morpho-genetical classification of the tropical plateau karstlands the following four head types are suggested:

1. Yangshuo type: Yangshuo or Jangso is a small town in the Kwangsi province of China, south of the town Kweilin. As a part of the Kwei-kiang karst region the karst "island mounts", the most imposing formations of their kind are to be found near to Yangshuo. /Figure 3./

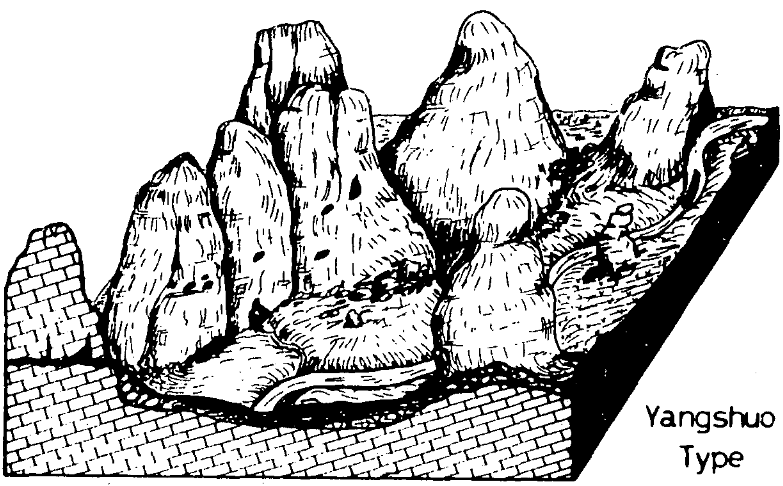

FIG. 3.

2. Órganos type: The name-giving type is to be found in the Sierra de los Órganos, Cuba, slightly to the north from the small town of Vinales, where the mogote karsts are. /Figure 4./

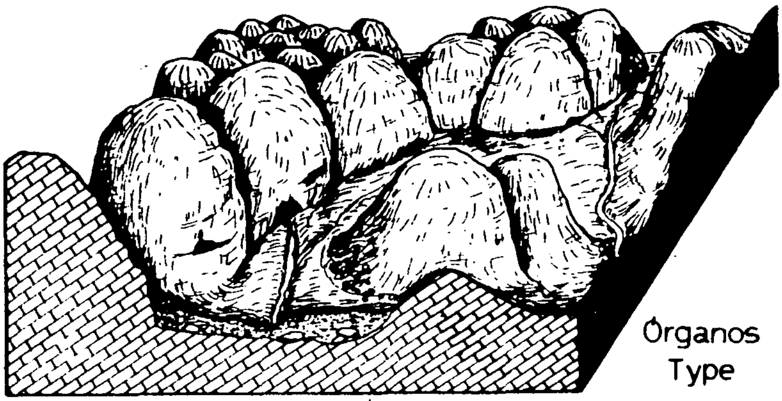

FIG. 4.

3. Sewu type: Gunung Sewu /"Thousand hills"/ karstic plateau is in Indonesia, in the Southern middle of Java, south-east of Jogjakarta. The area between the Wonosari Basin and the Baron Spring served for the more exact type determination. /In the geographical literature this area is mentioned as a typical specimen of "Kegelkarst" though the full forms to be found there do not resemble at all geometrical cones. That is why D. Pfeiffer renamed them "sinoids", and the karst-type "sine-karst"/. /Figure 5./

FIG. 5.

4. Tual Type. Tual is unknown as yet in the literature of karst morphology: it is a small settlement on the Kai-Ketjil island belonging to the Indonisian Maluku Archipelago. The island is built up of plio-pleistocene coral limestone and has undeveloped karstic phenomena /Figure 6./.

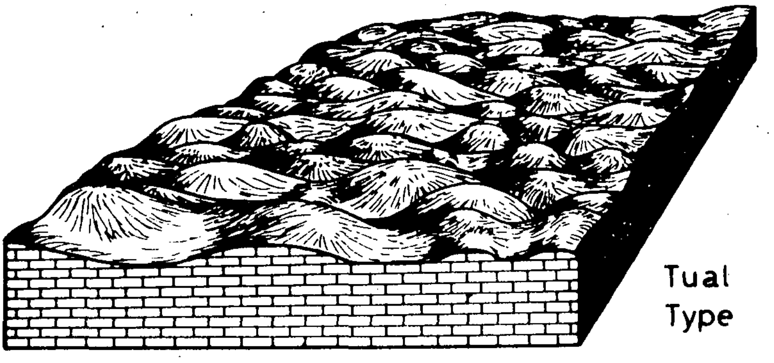

FIG. 6.

Comparative data of the four tropical head types:

	Morpho-genetic index	Relative height of full forms, meter	Number of full forms per km²
1. Yangshuo type	$<1,5$	100-300	5-10
2. Órganos type	1,5 - 3,5	50-200	10-20
3. Sewu type	3,0 - 8,0	30-120	15-30
4. Tual type	$>8,0$	10-50	0-50

The four head types do not indicate stages of denudation /see: Corbel/, but morpho-genetic units formed under different geological, climatological, hydrogeological conditions, during different periods. For instance it is obvious that the formation of the Yangshuo karstland took a substantially longer time than that of the Sewu type. Generally there is no genetic correlation between these types. For instance the Tual type will never develop into Yangshuo type.

In some cases it is difficult to decide of a certain karst region to which of the four types it stands nearest. In North-Vietnam and Laos for instance, there are many karst regions which form a transitory type between Yangshuo and Órganos. In such cases "Yangshuo-Órganos transitory type" is the suitable designation. Or in other cases: Órganos-Sewu transitory type, or again Sewu-Tual transitory type.

Within every head type of karst region it is possible to define sub-types.

Based on the correlation of the full forms two sub-types may be distingished:

1. Compact karst in which the full forms are in close connection /often enclosing depressions/, or close

2. Karst region with "island mounts", where the karst hills, because of progressed denudation, are isolated.

Further peculiar phenomena may be caused within one and the same morpho-genetic type by hydrogeological conditions:

a. the karst block lay near the receiving level /surface and underground drainage/, or

b. the karst is in an uplifted situation /mainly underground drainage/.

The characteristics enumerated may be demonstrated on the geomorphological map of the region.

To classify into the four head types some of the tropical karst regions, a table was prepared.

In the experience of the author there exist a few plateau karsts which cannot be classified in any for the head types or transitory types. These exeptional cases are not treated in this paper.

Classification of some tropical karstlands

Karst regions	Yearly precipitation	Average peadk height, meters a.s.l.	Age of limestone	Relative height of full forms, meters
I. Examples of the Yangshuo type karst				
Kwei-kiang and He-kiang Karst Regions, Kwangsi, China	1914	300-500	Carboniferous	100-300
Li-kiang Karst Region, Kwangsi, China	1472	300-500	Carboniferous	100-250
Lu-kiang Karst, SW of Nanning, Kwangsi, China	1322	300-600	Permian, Carboniferous	50-150
Middle Si-kiang Karst, Kwangsi, China	1200	80-200	Carboniferous	10-80
Tunnang-ho Karst, S. of Kwei-yang, Kweichow, China	1202	600-900	Permian, Carboniferous	80-200
SE Yunnan Karst Region, China	981	1500-2000	Triassic Permian	100-250
Bac-son Karst, Vietnam	1400	200-600	Permian-Carboniferous	100-200
Cao-bang Karst, Vietnam	1350	200-600	Permian, Carboniferous	100-200
Ha-long Bay Karst Region, Vietnam	1775	100-300	Permian, Carboniferous	50-200

Karst regions	Yearly preci-pitation mm	Average peak height, meters a.s.l.	Age of limes-tone	Relative height of full forms meters
II. Examples of the Órganos type karst				
Sierra de los Órganos N of Viñales, W-Cuba	1700	200-500	Cretaceous, Jurassic	50-200
Northern Littoral Mogote Karst, Puerto Rico	1200	50-200	Aymamon limestone /Middle--Tertiary/	50-100
Internal Cockpit Karst, Puerto Rico	1800	200-500	Lares limestone /Middle-Tertiary/	50-150
Cockpit Country, Jamaica	2500	300-600	White limestone /Upper Eocene-L. Miocene/	80-150
Sinamar-Kvantan-Takung Karst Region, Middle-W-Sumatra, Indonesia	2032	500-900	Carboniferous	100-200
Western Gunung Sewu, Middle Java, SE of Jogjakarta, Indonesia	1849	300-500	Miocene	50-120
Pangkadjene Karst, SW-Sulawesi, Indonesia	3545	100-300	Eocene	80-200
Maros Karst Region, SW-Sulawesi, Indonesia	3175	200-550	Eocene	80-200
Ajamaru Karst Region, Doberai Peninsula, W. Irian, Indonesia	4819	300-500	Miocene	100-200
Southern Yucatan Karst Mexico-Guatemala	2500	200-500	Oligocene-Cretaceous	100-200
Tabasco Karst Region, S. Mexico	4000	100-500	Cretaceous	50-150

Karst regions	Yearly preci-pitation mm	Average peak height, meters a.s.l.	Age of limes-tone	Relative height of full forms meters
III. Examples of the Sewu type karst				
Middle Gunung Sewu, Middle Java, Se of Jogjakarta, Indonesia	1809	200-400	Miocene	30-80
Kalapanunggal Karst, W. Java, Indonesia	3705	300-500	Miocene	50-150
Gunung Sewu of Karangbolong, Middle Java, Indonesia	3720	300-400	Miocene	50-120
Nusa Barung, Island of SE Java, Indonesia	1311	150-300	Miocene	50-120
Blambangan, SE Peninsula of Java, Indonesia	1367	250-350	Miocene	50-120
Bukit Badung /Tafelhuk/, S. Peninsula of Bali, Indonesia	1645	150-200	Miocene	50-80
Nusa Penida, island between Bali and Lombok, Indonesia	963	200-500	Miocene	50-150
Northern Sumba, Sumba Island, Indonesia	1895	500-600	Miocene	50-150
Middle Yucatan Karst, Mexico	1500	100-200	Miocene	50-100

Karst regions	Yearly precipitation mm	Average peak height, meters a.s.l.	Age of limestone	Relative height of full forms, meters
IV. Examples of the Tual type karst				
Kai-Ketjil Island, SE. Maluku Islands, Indonesia	2437	20-50	Plio-Pleistocene	10-30
Tanimbar Islands, SE Maluku Islands, Indonesia	1951	20-80	Plio-Pleistocene	10-50
Western Kobroör, Aru Islands, SE Maluku, Indonesia	2177	20-50	Plio-Pleistocene	10-30
North Bone Karst, SW Sulawesi, Indonesia	1642	250-500	Pliocene	30-80
Hitu Karst, Ambon Island, Maluku, Indonesia	3475	200-400	Plio-Pleistocene	50-100
North Yucatan Karst, Mexico	1000	100-200	Plio-Pleistocene	20-50
Middle and Southern Florida	1300	20-60	Miocene, Pliocene	10-30

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Gy. Dénes

DIE ROLLE DER ALLMÄHLICH ABGETRAGENEN WASSERUNDURCHLÄSSIGEN DECKE IN DER MORPHOLOGISCHEN ENTWICKLUNG DES KARSTES

Ein Teil der heutigen Karstgebiete war in der erdgeschichtlichen Vergangenheit bedeckt; die wasserundurchlässige Decke wurde erst später allmählich abgetragen. Derartige Prozesse können auch heute beobachtet werden, so z.B. in Ungarn im Karstgebiet von Aggtelek. Hier sei eine nähere Betrachtung dieses Prozesses gegeben und seine Rolle in der Verkarstung dieses Gebietes untersucht.

Wenn der bedeckte Karst in eine erhöhte Lage gelangt, wird die über dem Kalkstein liegende wasserdichte Decke durch äussere Einwirkungen, vor allem durch die auf ihr entstehenden Wasserläufe einer ständigen Erosion ausgesetzt, die diese Decke allmählich entfernt. Die früher bedeckte Kalksteinschnicht wird so schrittweise freigelegt, in erster Linie jene Gebietsteile, die dem am tiefsten eingeschnittenen und die Wässer dieses Gebietes ableitenden Tal zugewendet sind; dieses Tal bildet nun für den erhöhten Karst die lokale Erosionsbasis. Im Bett der dem Tal zugewendeten und in der wasserundurchlässigen Decke entstandenen Oberflächenwasserläufe wirkt nun eine lineare Erosion, die ebenfalls zur Freilegung des Kalksteins beiträgt; dann werden die herausragenden Elemente des verdeckten Kalksteinreliefs freigelegt. Nun kann die Verkarstung der entblössten Kalkoberschichte beginnen. Da die

Karsformen hier im Zuge der Zerstörung der wasserundurchlässigen Decke entstehen, tragen sie auch die Merkmale dieses Prozesses.

Die von der wasserundurchlässigen Decke auf die Kalksteinoberfläche treffenden Wässer suchen sich am Rande der Decke bzw. in dem im Bett der linearen Wasserläufe zutage tretenden Kalkstein einen Weg in die Tiefe: Es entstehen Ponore, welche die Wasserläufe an der Oberfläche vertikal anzapfen und in Richtung der Erosionsbasis unterirdische Karst-Wasserläufe bilden.

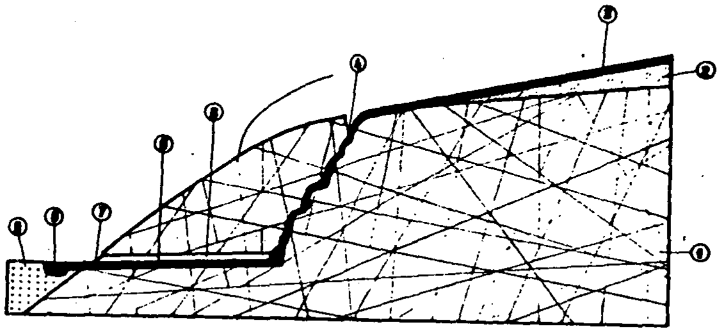
Die Zerstörung der wasserundurchlässigen Decke wird durch die Bildung der Ponor beschleunigt. Die von den Ponoren rückschreitende Erosion schafft neue Gräben in der Decke, deren Material sich nunmehr durch die Höhlengänge von der Oberfläche entfernt und durch die entstandene Schutterosion den unterirdischen Gang ständig erweitert.

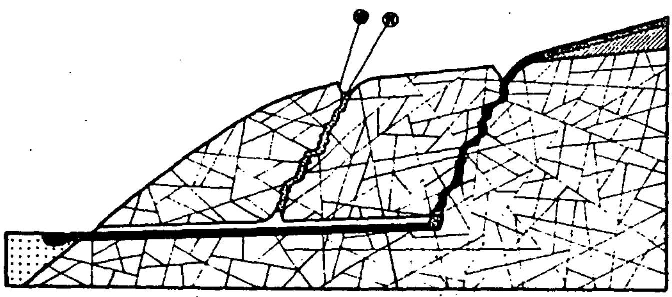
Während das Material der wasserundurchlässigen Decke in grossen Mengen sich durch die Ponore entfernt, werden weitere Kalksteingebiete freigelegt, und der Rand der verbliebenen Decke zieht sich immer weiter von den Ponoren zurück. Am neuen Karstrand entstehen neue Ponore und dieser Vorgang wiederholt sich ständig, während ein immer grösserer Abschnitt des Oberirdischen Laufes unter die Oberfläche gelangt.

Abhängig von der Nähe oder Ferne des den Karst entwässernden Tales, ferner abhängig von den Gesteinsverhältnisse und den tektonischen Gegebenheiten, entsteht in Richtung des die Erosionsbasis bildenden Tales ein neuer, selbständiger Höhlengang; oder aber der bereits vorhandene Höhlenabschnitt wird zur Erosionsbasis der durch den neugebildeten Ponor abfliessenden Wässer und der zum neuen Ponor gehörenden Gang schliesst sich dem vorhandenen Höhlengang an und verlängert ihn. In solchen Fällen spielen somit auch die Oberflächenverhältnisse in der Bestimmung der Richtung der Höhlengänge mit.

Verlieren nun die Ponore durch wiederholte Anzapfungen ihr Zuflussgebiet und ihre Wasserläufe, und trocknen aus, und gelangt auch kein neues Schuttmaterial mehr hinein, verwandeln sich diese Ponore in Schachthöhlen. Im Mittelgebirge jedoch werden diese ehemaligen Ponore häufig durch Schutt aufgefüllt, sie verstopfen sich und bilden Dolinen. Wenn nun die Dolinensohle mit wasserundurchlässigem Schutt ausgefüttert ist, kann ein Dolinensee entstehen.

Abhängig vom Kalkstein-Oberflächenrelief, das früher von einer wasserundurchlässigen Schicht bedeckt war, von der Spurlinie des Wasserlaufes an der Oberfläche der wasserundurchlässigen Decke und eventuell auch abhängig von den tektonischen Gegebenheiten sowie als Folge der allmähliche Abtragung der wasserundurchlässigen Decke und des ständig rückschreitenden Deckenrandes kann eine Dolinenreihe entstehen; aber auch vereinzelte Dolinen können sich aus ehemaligen Wasserschlingern gebildet haben. Gerade die unter der Oberfläche verlaufenden Spurlinie der Höhle sowie ihr innerer Formenschatz geben häufig Aufschluss darüber, welche Dolinen aus Wasserschlingern entstanden sind.





1. Kalkstein, 2. Wasserundurchlässige Decke, 3. Oberflächenwasserlauf, 4. Ponor, 5. Höhle mit Wasserlauf, 6. Höhlenbach, 7. Quelle, 8. Wasserlauf am Fusse des Kalksteinberges, 9. Schutt, 10. Doline, entstanden aus einem Ponor, 11. Ehemalige Ponorhöhle mit Schutt ausgefüllt.

Die fortschreitende Verstopfung beginnt meistens nicht im senkrechten Schacht des Ponors, sondern in dem dazugehörenden wasserlosen Abschnitt der horizontalen Höhlenganges. Meistens schliesst nämlich der Höhlengang des neuen Ponors nicht an der Schachtsohle des ehemaligen Ponors an der früher entstandenen horizontalen Höhlengang an, sondern an einem Punkt zwischen Quelle und altem Ponor. Auf diese Weise wird der waagrechte Gangabschnitt des ehemaligen Ponors bis zum neuen, wasserführenden Lauf langsam trockengelegt; der von der Oberfläche eingeführte Schutt füllt nun diesen zum Nebengang gewordenen, kein Wasser mehr führenden Höhlenabschnitt aus; dieser Nebengang folgt nicht der weiteren Vertiefung des Hauptganges und seine Sohle verbleibt im Verhältnis zum Hauptgang in erhöhter Lage. Die daraus herausgetretene Tonmenge weist meistens auf die Mündungsstelle des Nebenganges in den Hauptgang hin. Nach der Verstopfung des waagrechten Ganges füllt sich auch der ausgetrocknete senkrechte Schacht des Ponors. Kommt es zu einem oder mehreren Brüchen in dem vom Ponor ausgehenden vertikalen Höhlengang, so kann auch bei einem Knie eine Verstopfung eintreten.

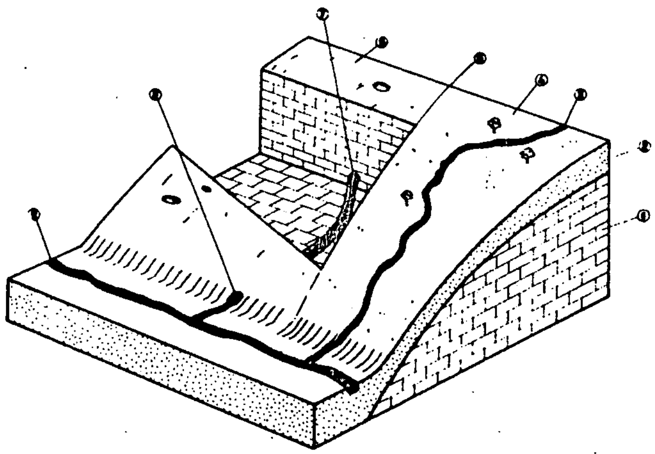
Prof. L. Jakucs hat den Zusammenhang zwischen dem nicht-karstigen Zuflussgebiet und der Breite einer Erosionshöhle nachgewiesen: zu grösseren nicht-karstigen Zuflussgebieten gehören breitere Höhlengänge, zu kleineren engere. Vergrössert sich das nicht-karstige Zuflussgebiet, verbreitert sich auch der Höhlengang, der sich stets dem maximalen Zufluss anpasst.

Ich bin der Ansicht, dass diese Regel im bestimmten Fällen auch im umgekehrten Sinne Gültigkeit hat, jedoch nur solang, bis die Öffnung des Ponors nicht gänzlich verschlossen wird, d.h. solange die Niederschlagwässer von einem noch so kleinen Zuflussgebiet Schutt mitführen.

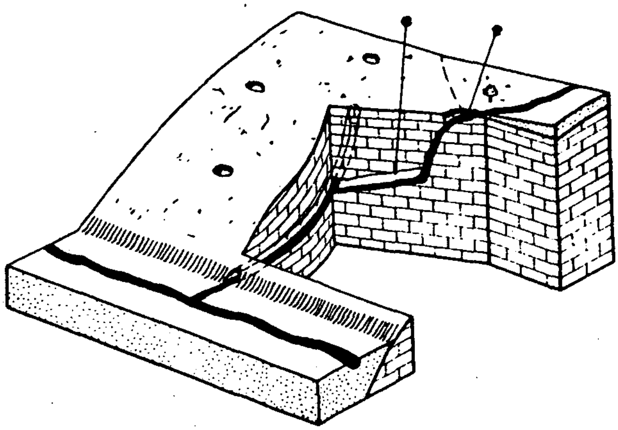
Verringert sich nun in solchen Fällen das Ausmass des nichtkarstigen Zuflussgebietes, wird auch die Geräumigkeit des dazugehörenden Höhlenganges, des dazugehörigen karstigen Wasserkanals geringer. Wenn das zum Ponors gehörige nichtkarstige Zuflussgebiet stärk schrumpft und der maximale Wasserzufluss nichtmehr die vorhandene Breite des Höhlenganges benötigt, gewinnt die Tendenz der Geröllablagerung die Oberhand. Das Geröll engt nun den Gang sowiet ein, dass die vom verbliebenen Zuflussgebiet stammenden maximalen Wassermassen Platz haben. Während nun eine Verbreiterung des Ganges mit der Entfernung des Gesteins verbunden war /Korrosion - Erosion/, schreitet die Einengung mit der Schuttablagerung einher.Das vollständige Versiegen des Zuflusses führt schliesslich zur vollkommenen Verstopfung des zum Ponor gehörenden ausgetrockneten Höhlenganges und des Ponorschachts.

Bei der Wasserversorgung der Höhle spielt selbstverständlich auch das karstige Zuflussgebiet eine Rolle, die jedoch während der Tätigkeit des Ponors kaum auffällt. Hört jedoch infolge der gänzlichen Verstopfung der Eingangsöffnung des Ponors auch der Schuttnachschub auf, wirkt sich langsam doch ununterbrochen die Tätigkeit der Sickerwässer aus - die bisher in Anbetracht der durch die Ponore herabstürzenden Wassermassen kaum auffiel - und es kommt in der Tiefe zur allmählichen Freilegung des verstopften Ganges. Und dieser Prozess kann mit der Zeit zur abermaligen Öffnung des Ponors führen.

Haben die Sickerwässer in der Tiefe den verstopften Höhlengang zumindest teilweise freigelegt, kann der Verschluss der Ponoröffnung - auf den auch die Niederschlagswässer einwirken - einstürzen. Befand sich Wasser in der Doline, so fliesst es ab und die so geöffnete Doline kann - wenn ihr ein minimales Zuflussgebiet verblieben is t - wieder als periodischer Ponor funktionieren, bis er wieder verstopft wird. Sollte infolge einer Oberflächenveränderung der sich öffnende Höhlenschacht seines gesamten Zuflussgebietes beraubt werden und kein neuer Schutt in den Schacht gelangen, kann es geschehen, dass der senkrechte Gang als Schachthöhle längere Zeit geöffnet bleibt.



1. Kalkstein, 2. Wasserundurschlässige Decke, 3. Oberflächenwasserlauf, 4. Ninht-karstige Oberfläche auf wasserundurchlässige Decke, 5. Karst-oberfläche der entblössten Kalksteinschicht, 6. Grenze zwischen kerstiger und nichtkarstiger Oberfläche, 7. Wasserführende Höhle im Karst, 8. Quelle am Bergfuss, 9. Wasserlauf im Tal.



11. Neue Ponor, entstanden nach Abtragung der wasserundurchlässigen Decke, 12. Neuer Seitengang der wasserführenden Höhle.

Die allmähliche Abtragung der wasserundurchlässigen Decke, die damit verbundene Verkarstung, das Entstehen der Ponore am Karstrand, ihre Verstopfung und abermalige Freilegung können in Ungarn im Karstgebiet von Aggtelek genau studiert werden. So ein Prozess führte auch zum Entstehen der Baradla-Höhle und der Béke-/Friedens/-Höhle. Die Schachthöhlen auf dem grossen Plateau des

Alsóhegy sind meiner Meinung nach ebenfalls aus Ponoren entstanden und auf die allmähliche Zerstörung der wasserundurchlässigen Decke zurückzuführen.

Zwischen den unter den beschriebenen Verhältnissen entstandenen ober- und unterirdischen Karstformen besteht ein enger Zusammenhang: Die aus Ponoren entstandenen Dolinen, Dolinenreihen, Dolinenseen und Schachthöhlen einerseits, sowie die Formenelemente der Höhlengänge und ihre Richtungsänderung anderseits, stehen genetisch in Wechselbeziehung.

Die am rückschreitenden Rand der wasserundurchlässigen Decke entstehenden Ponore, ihre Verstopfung und eventuell folgende Freilegung beweisen, dass die ihrer ursprünglichen Fuktion beraubten Karstformen früher oder später unbedingt verschwinden, bzw. sich den neuen Verhältnissen entsprechend verwandeln. Diese Gesetzmässigkeit bezieht sich auf die, aus einer früheren Verkarstung unter der Decke erhalten gebliebenen fossilen Formen, d.h. also, wenn sich die wasserundurchlässige Decke auf einer früher karstigen Kalksteinoberfläche angesetzt hat, verschmelzen die im Zuge der Zerstörung der Decke entstandenen rezenten Karstformen mit dem Formenschatz des freigelegten Urkarstes, der bisher unter dieser wasserundurchlässigen Decke begraben war; diese Formen werden nun entsprechend der neuen Fuktion umgewandelt und abgeändert.

Das Entstehen weitverzweigter Höhlensysteme ist stets ein polygenetischer Vorgang, dessen einzelne Komponente und Gesetzmässigkeiten in der Entwicklung durch sorgfältige Untersuchungen analysiert werden können.

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I. G a m s

A NEW METHOD OF DETERMINING THE KARSTIC SOIL EROSION

In contradiction to the surface karst forms the research of subsoil forms in limestone was neglected in the karst geomorphology. Mycroforms were studied mostly in relation to organic activity /Cousin, 1957; Smyth-Drzal, 1965/, bigger forms mostly in gypsum karst /Haefke, 1926, Penck, 1924/ or under calcarenite /Jannings, 1968/.

Behind the quarries where the soil was stripped off, different typical subsoil forms can be found in homogeneous limestone. The most common form is the covered Karren /solution grooves, lapiés/ and between them the Rundkarren. The holes in the rock have a diameter of some decimetres and are one or more metres deep. Their longest axes run in all directions, even in the horizontal ones. In the limestone surface apecial types of scallops occur; these are irregular in diameter and depth and are deeper on the gently inclined slopes than in the vertical walls. The covered kamenitzas, a kind of lapiés wells /"Geologische Orgeln", germ./ and covered bogaz and covered dolines with a depth of 1-3 m occur also under the soil cover. Many ten metres deep potholes, full of loam or clay, are opened in the quarry walls /Gams, 1971, in print/.

If the soil is eroded, many of these forms appear on the surface, constituing a proof of soil erosion.

A common feature of these subsoil forms is their smovther surface in homogeneous limestone. This smooth surface is significant for all the limestone surface under the soil. The smoothness is in inverse proportion to mechanical weathering and is diminishing in the upward direction. The degree of smoothness is smaller in nonhomogeneous limestone with fossiles or with recrystalized calcite or with chert inlayers, etc., with thinly bedded and fractured limestone. In mountain karst under the rendzina soil the limestone on the steep slopes has no smooth surface.

Contrary to smoother limestone surface under the soil the isolated stones standing out of soil have a more fissured surface, transected by rills and grooves and etched due to mechanical weathering and lithological differences. The degree of smoothness of the subsoil surface in limestone moreover is different but it is in a stady relation to the more dissected limestone surface in the open air. This difference between the surface originated under soil und that originated in the open air is still obvious after many hundred years where the soil level was artificially lowered and the subsoil forms came to be surface forms. The transformation of the surfaces is faster in Mediterranean climate than in the continental Karst of Slovenia.

The mentioned differences can be used as a method of determining the soil erosion. To be exact, the contact between the lower, smoother surface and the higher, more dissected, surface on the isolated stones in the semi-covered karst is a mark of how much the soil level is lowered.

The lowering can be caused by sheet denudation, washing of the soil particles by percolating water into the rock fissures or through them into the water channels. In tilled areas it can result also from subsidence of the soil after the deforestation and decomposition of the tree roots. If the wood trees cease to hold the soil particles above the empty fissures in the rock a strong downward erosion can take place.

The study of the soil erosion according to this method in many lots in the continental and Mediterranean karstic regions of Slovenia /NW of the Yugoslav Dinaric Karst/ included also the slope angle and mechanical texture of soil. The cadastral maps, the oldest made in the year 1925 and 1826, were used. Summarising the results the following conclusions can be presented.

The most intensive soil erosion is in the vineyards on the steep slopes. There the isolated stones with smooth surface protrude many decimetres above the soil level and are usually on the top cut off. In some places this cutting off is done to this day during the trench-ploughing; this occurs in different depths below the soil surface, but even as deep as 70 cm. Therefore the exact rate of soil erosion in vineyards can not be stated. Beside the karstic erosion in vineyards also the sheet erosion take place.

On the fields abondoned in the second half of the last century or at the beginning of the present century, the average height of the isolated sutt-off stones with smooth surface is 25-35 cm. The cutting off occured as deep as the ploughshare reached, that is 20-30 cm below the soil level. This work was done mostly in winter time, over a long period from the first settlement to the recent time. The last remnants of this work were observed in some villages in Dolenjsko in the first years after the World War II. The cutted-off stones were cleared away by building walls /Gams, 1967/, which are a typical features of the Mediterranean landscape. The stones were buried also in the bottom of the dolines, thrown into potholes or used for in building. In one particular case of the wall around an abondones field lot surrounded by uncleaned wood karst on classical /Trieste/ Karst it was established that 158 kg of limestone per 1 are were cleared eway from the soil the filde was being prepared for tilling /Gams, Lovrencak, Ingolic, 1971/.

In the fields where the cutting off took place 20 cm below the soil surface a century ago and where the cutt-off isolated stones protrude today 30 cm above the soil level, and where a rate of erosion of 0,5 cm per year must be reckoned with, are in the Slovene karst most frequent in the brown-to-red clay soil. This rate of erosion is lower than estimated by A. Horvat /1953, p. 50/ on the basis of old photos of the fields /1 cm per year/.

On meadows the stones were cutt off on the soil surface to make mowing possible. On the surfaces register in the cadastral map already in 1825 as meadows the cutt-off stones are today 12-22 cm high. Stones that are higher and were not cutt off, have on the top a more dissected surface originated in the open air. It remains an unsettled question whether this erosion is due to older tilling or to the soil erosion taking place also under the grasscovered karst surface.

The smooth limestone surface originated below the soil but now in the open air have been found in many places also in the present-day woods. In such cases the soil erosion may be explained through the burning down of forests for gaining pastures in the Middle Ages or earlier. Destroyed along with the forest were also the whole rendzina and roots in it. In some wood lots the cutt-off stones prooves a ahondoned meadow.

The following factors that influence the erosion intensity are obvious. The clay soil is subject to a more intensive erosion than the sandy soil. This is probably due to a more intensive fissuring during the dry summer. The clay soil of the terra rossa type has namely a high heat conductivity, and where it is without a vegetation cover its temperature is in the depth of 15 every month in the year higher than the mean daily value for the soil surface /Tommasini, 1971/. After heavy storms these fissures are filled with down-washed soil.

Outside the vineyards the slope angle has only a seeming role for the soil erosion in field terraces. On the slope between two terraces the soil was dug out and transported on the terrace below. There the isolated stones with smooth surface are the highest. On the other fields and meadows no correlation between slope angle and erosion intensity could be traced. This is in accordance with the absence of bigger accumulated forms below the meadows and fields on gently inclined slopes and with the absence of gully erosion forms. The lowering of the soil level is therefore presumably a consequence of the vertical downwash.

The results of our investigation provide an explanation for the numerous differences between the bare Mediterranean karst and the more covered, inland, karst in the limestones of Dinaric Karst. The differences are based also on the older and denser settlement and older agriculture in the Mediterranean karst. But the tilling of the shallow clay soil in the inland karst leads to the some fate: to the bare karst stage. The results of studying the soil erosion on the karst are interesting also for the conservation of soil and nature. If the annual rate of soil erosion in some soil type is half a centimetre per year, then the tilling or the soil has to be reduced in favour of other kinds of land use. As a matter of fact the diminishing of tilled surfaces in the Yugoslav dinaric countries is progressing rapidly and the soil erosion estableshed by our method is one the causes of this process. Even the local people know that in their fields the isolated stones "grow up", as they say.

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L. Jakucs

THE KARSTIC CORROSION OF NATURALLY OCCURRING LIMESTONES IN THE GEOMORPHOLOGY OF OUR AGE

During recent years the theory of karst corrosion has been considerably modernised, partly due to the new interpretations of the processes resulting from the rapid development of chemistry, partly, however, as a consequence of the ever-increasing mass of karst research data. Thus, the zonal and extrazonal richness of form of the karsts genetically can today be explained only on the basis of the accurate knowledge of the nature and extents of the processes involved. Contributions have been made to the develppment of certain aspects of the theories of dissolution by the results of Hungarian research, including those of the present author. Hence, the review of this subject was considered justified.

The concept of karst corrosion is taken to understand primarily the particular dissolution denudation processes of limestones /and also, in a wider meaning, those of other limestones which dissolve well in water without a residue/.

In connection with the dissolution of limestone in water, three quite different processes must be considered. First, a distinction must be made between carbonate dissolution in pure /distilled/ water, and hydrocarbonate dissolution, that is the dissolution of limestone in water containing carbon dioxide. There are specific qualitative and quantitative differences between the two, but both processes are reversible. The third type of dissolution involves the participation of other chemical agents, mainly organic and inorganic soil acids, etc. In this latter case the new calcium compound formed in solution is generally no longer able to reform $CaCO_3$.

I. The carbonate dissolution of limestone

When limestone /$CaCO_3$/ dissolves in distilled water, its dissociated ions remain unchanged /apart from solvation/, and the act of dissolution can be expressed by the following reversible reaction:

$$CaCO_3 \rightleftharpoons Ca^{2+} + CO_3^{2-} \qquad /1/$$

An equilibrium is established between the solid phase /$CaCO_3$/, the solvent /H_2O/ and the dissolved ions, and this can be defined by the solubility product K_1 /TILLMANS 1942, MILLER 1952/. K_1 is a variable index, the absolute value of which generally changes linearly with the temperature of the solution, but it also depends on certain crystal-structural properties of the solid phase. The K_1 for the rhombic dipyramidal modification of $CaCO_3$ /aragonite/ is higher than that for the trigonal calcite /SCHOELLER 1956/.

Table 1 is a collection of the literature data which give the absolute and variable orders of magnitude for K_1.

Table 1

Author /year/	t /°C/	dissolved $CaCO_3$ in mg/l		
		calcite	aragonite	amorphous $CaCO_3$
SCHLOESING[x] /1872/	8,7	10,0	-	-
SCHLOESING /1872/	16,0	13,1	-	-
SCHLOESING /1872/	25,0	14,3	-	-
CHARLOT-ENSCHWILLER /1939/	-	12,4	-	-
TROMBE /1952/	16,0	16,0	-	-
HODMAN /1955/	cold	14,25	-	-
HODGMAN /1955/	warm	18,75	-	-
SCHOELLER /1956/	25,0	14,33	15,28	14,45
SCHOELLER /1956/	50,0	15,04	16,16	15,15
SCHOELLER /1956/	100,0	17,79	19,02	18,16

[x] The pedological wark of SCHLOESING, which appeared in 1872, is not known in the original in Hungary; nevertheless its data are frequently cited by Western authors, e.g. O. LEHMANN /1932/, TROMBE /1952/, etc. The data of SCHLOESING in the Table are therefore given only on the basis of secondary sources.

The views to be found in the literature regarding the time-requirements for the dissolution of limestone in pure water are fairly contradictory. According to HARRASOWITZ 1954, BÖGLI 1956, 1960, H. LEHMANN 1956, 1960, BAUER 1964, FRANKE 1967, etc., the reaction concerned must be extremely fast. This conclusion was based on the fact that when the above authors analyzed samples of water collected from limestone surfaces during field-studies they were unable to detect dissolved $CaCO_3$ in concertrations lower than those given in the Table. BAUER /1964/, for example, collected for analysis the moisture trickling down "in statu nascendi" in a karr-channel; this had been in contact with the surface of the limestone for only a few seconds. Accordingly, BÖGLI /1960, 1963/ denotes the time-requirement for non-carbonate primary dissolution as about 1 second. /See also later in connection with the hydrocarbonate dissolution./

In the view of MARKÓ /1963/, however, these experimental results confirm not the high rate of dissolution, but the fact that the ion-diffusion under the special experimental conditions was particularly rapid; nevertheless, the rate of this process, like the dissolution of all solid substances, is controlled primarily by the rate of diffusion of the dissolved molecules or ions from the saturated solution layer in the vicinity of the surface of the solid phase to the more distant solution layers. It is natural, therefore, that the diffusion conditions will be optimal in a thin liquid film flowing over the surface; in accordance with the MARKÓ interpretation, this can explain the greater intensity of the dissolution dynamics.

At the same time, however, GERSTENHAUER and PFEFFER /1966/ go still further and, on the basis of their own extensive investigations, directly cast doubt on the reliability of BÖGLI's analytical data. They had collected limestone samples from various places throughout the world, and checked their time-curves under sterile laboratory conditions; they did not observe such a rapid achievement of saturation, but instead /as shown in Figure 1/ times which were longer by several orders of magnitude. In some samples for example, the time during which the sample was in contact with the water, and which was necessary to attain a solubility of 13 mg/l, was a whole day; this is even more surprising, because the water used contained a little carbon dioxide, which normally accelerates the dissolution.

The cause of these sharp, apparently irreconcilable differences here lies almost certainly in the different chemical investigation methods used by the various authors. Without going into details /these are given by MERCK, MÜLLER and GERSTENHAUER/, it must be pointed out that BÖGLI and FRANKE titrated their water samples by the WARTHA-LUNGE method with methyl orange as indicator, whereas GERSTENHAUER and PFEFFER used titriplex III /chalconecarboxylic acid/. The viewpoint of GERSTENHAUER is in all probability closer to the truth, because the indicator used is definitely calcium-specific; it reacts only with Ca^{2+} ions and gives a reliably clear colour change at the end-point even with quite weak solutions.

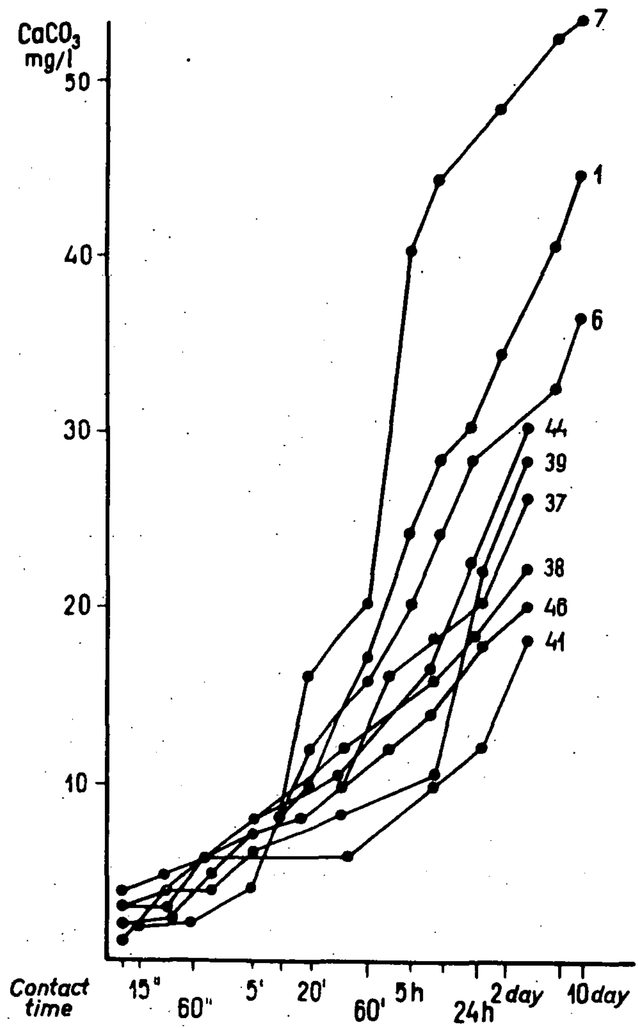

Figure 1. Time courses of the dissolution of various types of limestone in water saturated with atmospheric CO_2 /according to GERSTENHAUER and PFEFFER/.

This carbonate dissolution process is of fairly subordinate practical importance in nature of course, at least directly. Completely pure /quasi-distilled/ water does not exist under the geographical conditions leading to karstification. The freatic waters which must be considered from the point of view of actual karstic corrosion /but rain-water too/ always contain certain amounts of dissolved chemical substances, and the variable amounts and compositions of these change the capacity to dissolve carbonate in a decisive way.

Of these factors, the role of <u>the carbon dioxide saturation of the water</u> is stressed in the literature, since water containing only a little carbon dioxide will dissolve many times the amount of limestone dissolved by the same volume of pure water.

II. <u>The hydrocarbonate dissolution of limestone</u>

The dissolution of limestone by carbonic acid is termed hydrocarbonate dissolution, because the carbonic acid ions present in the solution react with the limestone to yield the well-soluble calcium hydrocarbonate, $Ca/HCO_3/_2$ /KYRLE 1923, TILLMANS 1932, etc./.

<u>The factor controlling the dissolution of limestone as hydrocarbonate, and the opposite of the dissolution process, the redeposition of the limestone from the solution, is in all cases the carbon dioxide /carbonic acid/ concentration of the water /or solution/ concerned</u>. To a first approximation it can be said that the water in contact with the limestone is capable of dissolving more $CaCO_3$, the greater the concentration of the CO_2 previously dissolved in it.

If the CO_2 content of the water in contact with the limestone is increased, therefore, the amount of limestone dissolved will increase, while if the carbon dioxide leaves the solution /e.g. by evaporation/, the dissolved limestone content of the solution will decrease by means of its precipitation from the solution and its accumulation /lime-muds of chemical origin, stalactites, stalagmites, travertine, etc. are formed in this way/.

The total dissolved CO_2 content of some natural water may vary considerably, and since there is a direct connection between the CO_2 content of the water and its ability to dissolve carbonate <u>in order to interpret the corrosion dynamism of the given water it is of the greatest importance to study all those factors which affect the amount of CO_2 dissolved by the water in contact with the limestone</u>.

The following equilibrium is involved:

CO_2 /in the gas-space/ $\rightleftarrows$ CO_2 /absorbed in the water/ /2/

The amount of carbon dioxide absorbed is affected by the following factors:

1. The carbon dioxide concentration of the gas phase in contact with the water. This is expressed by the <u>partial pressure</u> of the carbon dioxide /p CO_2/.

2. The mutual temperature of the water and of the gas, at which the process of dissolution occurs.

3. The hydrostatic pressure acting jointly on the water and the gas phase in contact with it.

4. The amount of time available for the dissolution process.

Thus, it can readily be seen that the dissolution of gaseous CO_2 and the decomposition of the solution /reformation/ depend in an extremely complex way on the combination of the above factors, for the change of any one of them can displace the equilibrium in either direction.

Although the conditions controlling the dissolution of CO_2 in nature are so complex, it is nevertheless worthwhile, for the sake of clarity, to consider the above four points separately.

It should first be pointed out that in accordance with the HENRY-DALTON law /1803/ the amount of the gaseous component dissolving in the liquid phase in contact with the gas is directly proportional to p, the partial pressure of that component, and is inversely proportional to the change of temperature. Thus, the amount of CO_2 dissolved in the water can be determined with the help of the following formula:

$$\text{dissolved } CO_2 \text{ in g/l} = L \cdot p \cdot 1.9634 \qquad /3/$$

where the value 1.9634 is the reciprocal density of CO_2 in l/g, p is the partial pressure of the CO_2, and L is the <u>solubility</u> or <u>absorption coefficient</u> for the CO_2 gas, which varies with the temperature. Table 2 contains the values of L for the more important temperatures involved in the karstification.

Table 2

	dissolution temperature, °C							
	0	5	10	15	17	20	25	30
L =	1,713	1,424	1,194	1,019	0,958	0,878	0,765	0,665

Equation /3/ was used as long ago as 1872 by SCHLOESING, who calculated and tabulated the amounts of carbon dioxide to dissolve in water at given temperatures and p CO_2 values. The most relevant of his values are given in Table 3.

It can be seen from Table 3 that at 5 °C, for example, with a typical p CO_2 value for the atmosphere of 0.0003 /0.03 % carbon dioxide content/, the moisture in contact with the air is capable of absorbing about 0.84 mg/l carbon dioxide. At higher temperatures, for instance at 30 °C, which occurs in Hungary too during the summer, but which is general in the tropics, the amount of CO_2 absorbed is less /0.39 mg/l/.

Table 3

The change of the CO_2-dissolving capacity of water wiħh the temperature and p CO_2 values occurring in practice

p CO_2 in the atmosphere	TOtal CO_2 dissolved in the water /in mg/l/, at the following temperatures							
	0 °C	5 °C	10 °C	15°C	17°C	20 °C	25° C	30 °C
0,0001	0,34	0,28	0,23	0,20	0,19	0,17	0,15	0,13
0,0003	1,01	0,84	0,70	0,60	0,56	0,52	0,45	0,39
0,0005	1,68	1,40	1,17	1,00	0,94	0,86	0,74	0,65
0,00075	2,52	2,09	1,76	1,50	1,41	1,28	1,12	0,98
0,001	3,36	2,80	2,34	2,00	1,88	1,72	1,49	1,31
0,0015	5,04	4,19	3,51	3,00	2,82	2,58	2,24	1,96
0,002	6,73	5,59	4,69	4,00	3,76	3,45	3,01	2,61
0,0025	8,40	6,99	5,85	5,00	4,70	4,28	3,72	3,28
0,005	16,8	13,98	11,7	10,0	9,4	8,57	7,46	6,56
0,0075	25,2	20,9	17,6	15,0	14,1	12,8	11,2	9,79
0,01	33,6	28,0	23,5	20,0	18,8	17,2	14,9	13,1
0,02	67,3	55,9	46,9	40,0	37,6	34,5	30,0	26,1
0,03	101,	83,9	70,4	60,0	56,6	51,7	45,1	39,2
0,04	135,	112,	93,8	80,1	75,6	69,0	60,0	52,5
0,05	168,	140,	117,	100,	94,1	86,2	74,6	65,3
0,06	202,	168,	141,	120,	113,	103,	90,0	78,4
0,07	236,	196,	164,	140,	132,	121,	105,	91,4
0,08	269,	224,	188,	160,	151,	138,	120,	104,
0,09	303,	252,	211,	180,	169,	155,	135,	118,
0,1	336,	280,	235,	200,	188,	172,	149,	131,
0,2	673,	559,	469,	400,	376,	342,	300,	261,

At the same time, however, it is true that in the tropics, where an intense CO_2 production takes place during the entire year as a result of the decomposition of the rich organic matter and also because of other soil and biogenetic processes, the carbon dioxide content of the air in the vicinity of the soil can attain values somewhat higher than the average. For example, LEHMANN /1955/ determined a value of 2.5 mg/l for the CO_2 content /thought to be of atmospheric origin/ of rain-water collected from air at temperature of 22 °C. This would correspond to a partial pressure of CO_2 in the atmosphere of about 0.0016 according to the SCHLOESING tabulation /Table 3/ /H. LEHMANN 1956/.

The surprisingly large atmospheric carbon dioxide content calculated from this /0.15 %/, however, was not controlled directly by means of a simultaneous air-analysis, and so the relatively really high dissolved CO_2 value can not be sufficiently convincingly documented as being exclusively of an atmospheric diffusive origin. It is not excluded, for example, that the CO_2 content of the water may have been increased by the mixing with it of fine particles of <u>spray arising from the high-energy collision of the rain-drops with the soil</u>, since it is known that the water component of the aerosols so formed contains ions from the soil in relatively high concentrations /CAUER 1954, JAKUCS 1953, 1959/. A further contributory factor may be that the p CO_2 values of the rain are determined not by the observed temperature of the precipitation zone, but by the much lower temperatures prevailing at the cold vapour-condensation cloud level at a height of several thousand metres.

The fact that the factors mentioned almost certainly do modify the chemical composition of the rain-water collected fairly close to the soil surface, and to a considerable extent /an order of magnitude due mainly to the aerosol factor/, in supported by similar water-analysis results from the temperate zone, and even from high mountains. Such studies were carried out in the Alps by BÖGLI /1960/ and BAUER /1964/, and in Hungary by CZÁJLIK /1961/. Practically agreeing amounts of carbon dioxide were found volumetrically in rain-water samples collected above the soil /in the range 1.32-3.63 mg/l CO_2/.

Of course, one can hardly talk of a very significant hydrocarbonate dissolution of the limestone even in the presence of 2-3 mg/l dissolved CO_2, for /as can be seen from Table 4/ in order for the water in contact with the limestone to dissolve sufficient of it as hydrocarbonate so as to accord with the simple dissociation given in equation /1/, i.e. about 13 mg/l $CaCO_3$, a dissolved CO_2 content of about 6 mg/l would be necessary at 17 ^{o}C; this is equivalent to approximately ten times the p CO_2 to be found in the atmosphere.

In contrast with this, the actual dissolved CO_2 content of the soil waters and karst waters occurring in nature, and which are responsible for the karstic corrosion, is in fact always many times higher /it is very often more than 100 mg/l even!/. <u>There is no doubt that the rain-water which falls onto the soil obtains this high carbon dioxide concentration not from the air, but from the soil itself.</u>

The fact that soils, and thus the soil species covering limestones too, possess a soil atmosphere with a high p CO_2 value, was demonstrated long ago by pedological research workers /SCHLOESING 1872, FODOR 1875, WOLLNY 1880, BOUSSINGAULT and LÉVY 1853, etc./.

The study of the soil atmosphere, that is the gas mixture occupying the pore volume in soils with looser structures, is dealt with in detail later. At this point, however, it should be mentioned that the pedological investigations have indicated a CO_2 content of more than 1 % in the atmospheres of humous soils rich in organic matter, while it may frequently even be more than 10 %. This must be regarded as the most decisive factor governing the dynamism of the karst corrosion, for the rain_water falling onto the soil surface and absorbed there will be affected immediately by the soil air which comes into contact there on a very large surface with the water adhering to the soil particles, and thus even in the uppermost soil layer the water will become saturated with carbon dioxide in accordance with the p CO_2 value of the gas mixture there.

The very important role of the soil atmosphere in regulating the dissolution of the limestone was also observed relatively early by geographers investigating the genesis of karsts. KNEBEL analyzed the interaction quite comprehensively as long ago as 1906, but the relations between the dissolving power of the water and the soil had been considered long before him. For example, in 1831 the Hungarian VASS had given an already detailed account of the stalactite and stalagmite formation theory of PARROT, IANG and SOMMER, which is a reasonably good approximation to the presently accepted scientific view. According to VASS, these researchers explain the stalactite formation by the dissolving work of the rain-waters seeping through "the layer of decayed plants and vegetable mould which is saturated with carbonic acid".

CHOLNOKY /1940/ also stressed the role of the carbon dioxide of the soil in the aggressiveness of the water: "It is known that a constant decay and a slow oxidation take place in the soil, with the formation of carbon dioxide. This is then concentrated on the soil particles, since these always have gas-concentrating natures. If it begins to rain after dry weather, the "smell of rain" can be detected. This is the characteristic smell of those gases which are expelled from the surface of the particles of soil. It can be demonstrated that at such time there is very much gaseous carbon dioxide in the lower layers of the air of the wetted area. Here, therefore, much gaseous carbon dioxide gets into the fallen rain-water, especially as a result of the dynamic pressure of the colliding rain-drops. This considerable amount of gas is carried by the water into the cracks in the rock." /op. cit. p. 1006./

The measurements of TROMBE and of JACKLY in France and Switzerland /TROMBE 1951, 1952, 1956/ indicated that the localization of CO_2 gas in the soil layers covering the karst formations can reach proportions /10-25 %!/ which are never observed otherwise in the atmosphere.

Very extensive and thorough studies were carried out in Hungary by FEHÉR /1954/ in order to discover the variations of the CO_2 content of the soil atmosphere and the regularities involved, while the present author also made measurements on Hungarian and Yugoslav karst soils in 1967-8. The results of all these investigations show that <u>the composition of the soil atmosphere reacts with very rapid and sensitive changes to both the macro- and microclimatic factors, and characteristic simultaneous</u>

differences are shown even within a given study site /e.g. a single sink-hole/, depending on the type of vegetation living in the soil, and even on the individual species in the rhizosphere /between the roots of the plants/ JAKUCS 1970, 1971.

It clearly emerges from what has been said that the permeating waters originating from the rainfall, which direct the entire karst development by means of their dissolution of the limestone, acquire their carbonic acid content /which determines the dynamics of the corrosion/ essentially always and everywhere in the uppermost layer levels of the soil. This means therefore that in a certain region the rate of the corrosion karst-denudation is controlled most importantly by /in addition to the amount of rain-water seeping through/ the biological and other soil-development processes in the thicker or thinner layer of soil covering the surface.

It should be mentioned that in the interior of the lithoclase network the water seeping into the network of cracks in the limestone from the surface humous soil layers no longer has the possibility to come into contact with gases whose compositions are significantly different qualitatively or quantitatively from that of the soil atmosphere. Thus, the carbonic acid values obtained in the soil are retained by the water almost unchanged as it seeps through right to the well ventilated cavern, or again emerges at the surface, where the new environment causes the evaporation of the dissolved carbon dioxide brought by the water to give a new equilibrium corresponding of course to lower p CO_2 values.

The temperature of the water seeping down under the action of gravitation in the lithoclase system in the interior of the maturing karstic limestone mass is practically unchanged during its passage as a rule. It is known that the vertical systems of crevices in which the water trickles down are at the same time the means for thermal exchange by convection; these can ensure the uniform temperature corresponding to the yearly average for the region almost perfectly in the entire system above the karst water level. In this way, the thermal factor can have an effect on the CO_2 content of the water more or less only in the upper soil zone of the infiltration, where its action is exerted in accordance with the values given in Table 3.

It must be noted, however, that compared to the effect of the partial pressure differences the role of the soil temperature differences which occur in nature in practice and which quantitatively effect the CO_2 dissolution is much smaller, even in extreme cases; at any p CO_2 level whatever, water at 0 °C is able to dissolve only about twice as much as that dissolved by water at 20 °C. Thus, in the karst dynamic evaluation of the role of the thermal factor, in agreement with the majority of the present climatic karstmorphogenetic authors /H. LEHMANN, TROMBE, BÖGLI, WISSMANN, GVOZDETZKII, etc./, the correct procedure is probably to conceive the effect of the temperature levels characterizing the individual climate zones of the earth not in the direct SCHLOESING sense, but as an indirect effect composed of the increase of the material transport per unit time /intensity of dissolution/, soil atmospheres containing more CO_2, and more intense soil processes assisted by the higher thermal level.

For example, the warm rain in the tropics /because of its higher temperature/ is able to absorb less CO_2 gas than the cold water from melted snow in the polar regions for instance. This greatly overrides and subordinates the fact that at the same time the dissolution process is faster in the tropics because of the higher temperature, while the production of carbon dioxide is much more vigorous as a result of the intense inorganic and biogenetic soil processes. As the final complex resultant here, therefore, the possibilities of the high-level saturation of the water with CO_2 will nevertheless be much more favourable.

We have now arrived at the possibility of taking up a well-founded clear stand in the international controversy which arose following the ominous attitude of CORBEL /1959/: it is not CORBEL, but H. LEHMANN and the climatic geomorphologists following in his footsteps who are right. These latter not only recognise temperature and precipitation-order differences in the climate factor, but with a real DOKUCHAYEV-ian attitude can take into account each of the geomorphological, pedological, biological, hydrological, chemical, etc. factors resulting in the climatic zonality, and also their simultaneous complexity even /JAKUCS 1970/.

We have so far studied the roles of the partial gas pressure and the temperature from among the factors determining the capacity of the water to absorb carbon dioxide from the atmosphere or the soil-air. It still remains, therefore, to analyse the pressure and time factors.

It is not necessary to provide a special proof that the ability of water to absorb CO_2 increases with increasing pressure. It is sufficient to point to the clear example of soda-water, which provides a striking experimental confirmation. It is less well known, however, that among the natural actualities of karsts the possibility of the development of the pressure factor is ensured by the periodicity of the rainfall, water or soil atmosphere penetrating from the karst soils into the lithoclases of the limestone, depending on whether there is an ample surface water supply or a lack of it.

When there is a very rainy period the cracks in the limestone fill with water. However, if these filaments of water running down under the action of gravity can no longer obtain a continuous replacement during a drier period, then their continuity is interrupted; a weak vacuum forms and air from the soil is sucked into the network of cracks.

When it again rains, of course, the "entrances" above the lithoclase network soil again become covered with water, and this now forces the gas mixture already in the cracks to greater depths.

The cracks are frequently so thin that the laws relating to adhesion and capillary attraction overcome the forces striving to arrange the system according to density. Thus, alternating gas and liquid phases migrate downwards, somewhat similarly to what can be seen in a thermometer with a broken mercury thread.

Even in this stage certain hydrostatic pressure modifications will affect the equilibrium of the water - gas system, since if there would be no pressure distortions arising from the gravitational and adhesive forces in the system of cracks, then the water there would not move downwards. These pressure changes, however, are still not so significant that they would substantially modify the water - carbon dioxide phase-equilibrium formed in the soil. Nevertheless, the water sooner or later reaches a level where there is no longer a free, empty route towards the depths. This is either because the sub-layer is impermeable and so there is no network of cracks, or because the existing network is already filled with water. The arriving water therefore finds its path blocked, begins to build up, and together with the accompanying air bubbles is forced to seek an outflow possibility in the lateral directions.

This is not easy, because the cracks, which now should lead away the water in the three-dimensional network to the karst level in the horizontal directions, that is superficially or linearly, are themselves no more developed or wide at the beginning of the karst maturation than the vertical lithoclase system. The water units /and also the gas bubbles between them/ are therefore compelled to enter zones where the hydrostatic pressure increases strongly. The pressure here will be higher, the greater the water supply from the surface and the lower the possibility for lateral movement. Thus, a karst water zone flowing at high pressure develops in the interior of the karsts /JAKUCS 1960, 1968a, 1968b/, in which the water will become enriched by further amounts of dissolved carbon dioxide, since the pressure is also exerted on the gas mixture, and this is now practically compressed into the solution.

In this zone, where the spaces and cracks in the rock which ensure the passage of water are now filled with water, a pressure of several atmospheres may result /mining observations!/. The pressure is particularly considerable <u>in the</u>

lower level of the karst water zone where the movement is horizontal. Experience has shown that it is not rare, especially in the case of young karsts, for the pressure to exceed 10 atmospheres even.

We shall return to this question later, but in connection with the magnitude and effectiveness of the role of the pressure it must be noted here that this comes about essentially via a certain modification of equation /3/. According to the classical gas law of BOYLE-MARIOTTE, the volume of a given mass of gas measured at various pressures is inversely proportional to the pressure. The factor 1.9634 given in equation /3/ is therefore not a constant value, but is valid only for the case of a pressure of one atmosphere. For a pressure of 2 atmospheres this factor must be doubled, for a pressure of 10 atmospheres it must be multiplied by 10, and so on, since the weight of the gas too has increased in these proportions as a result of the compression.

Let us now assume a case where the value of p CO_2 does not change, that is the composition of the gas mixture remains constant. Then, in the gas mixture - water system at 10 ^{o}C and a pressure of 5 atmospheres with p CO_2 = 0.002, the total amount of CO_2 gas absorbed by the water will increase from the value 4.69 mg/l given in Table 3 to a value of $1.194 \cdot 0.002 \cdot 5 \cdot 1.9634 = 23.45$ mg/l. Since this number is exactly five times the amount of CO_2 dissolved from the air at a pressure of 1 atmosphere, it might be said that up to a certain limit the capacity of water to dissolve CO_2 varies with the pressure in accordance with the product of the capacity at 1 atmosphere and the number of atmospheres /HENRY's law/.

At the same time, it is essential to bear in mind a very important factor, which can modify the validity of the above hypothesis considerably under karstic conditions. This is the fact that as a result of the effect of pressure the composition of the original gas space changes in the closed two-component system in the interior of the karst, in so far as the greater the pressure, the less the partial pressure of CO_2 in the gas space. This is related with the fact that the absorption coefficients /L/ of different gases are not the same. Those of the gases playing the most impartant parts in the gas space are substantially smaller than that of CO_2 /for oxygen at 20 °C L = 0.031; for nitrogen at 20 °C L = 0.015; and for carbon dioxide at 20 °C L= 0.0878/.

This has the result that with the increase of pressure the carbon dioxide is relatively quickly exhausted from the heterogeneously composed gas system, and the higher pressure values are practically powerless to increase still further the total CO_2 content of the solution. Because of this it is our opinion that as regards the increase of the karst water it is the earlier pressure increases /e.g. from 1 to 10 atmospheres/ which play the essential role, the unit pressure increases for hydrostatic pressures of up to even 100 atmospheres on the deep karst waters having much lower effects on the direct increase of the dissolution.

As a result of the differences in the absorption coefficients for the three gases, it is understandable that the composition of the original gas mixture is finally very changed, and at extremely high pressures it consists almost exclusively of the most difficultly soluble nitrogen. /This is why nitrogen always predominates in the gas bubbles coming to the surface with the waters of karst springs rising form great depths, for example at Miskolc-Tapolca, in the warm springs in Buda, etc./

It may explicitly be stated, therefore, that the fact of the extensive increase of the dissolved CO_2 as a result of the increase of the hydrostatic pressure is very important from the point of view of the development of the karsts, because the state of the karst corrosion level /the embryonic cavern formation level/ in the depths is indicated by the practically secondary aggressivity of the water.

It is plausible that with the later release of the pressure, when the water reaches a wider cavity or surface where its directions of movement are determined by the slope, the gases compressed into it in the pressure zone will come out of solution; this is also accompanied by the cessation of the secondary hydrocarbonate dissolving capacity.

In such places, however, the water is as a rule not only released from the hydrostatic load, but at the same time also comes into an environment where the p CO_2 is much lower than in the infiltration soil zone. Thus, further CO_2 will leave the solution in accordance with the differnce in p CO_2 values for the two air spaces, until a new equilibrium has been established corresponding to the p CO_2 /and temperature/ of the new air space as governed by equation /3/.

In the literature one can find the evaluation of the role of pressure from a different viewpoint. Thus, of the Hungarian authors particularly DUDICH /1932/, CHOLNOKY /1940/ and KESSLER /1938/ long ago stressed the importance of the changes in the surface tension of the water. It is a matter here of the tensile force occurring as a result of the surface tension on the outer surface of the water drop moving from the crevice in the rock to the ceiling of the cavern, and also of the surface pressure decreases affecting the karst waters flowing on the convex slope and reduced to spray in the waterfalls. These factors simplifly and accelerate the diffusion of the excess CO_2 into the gas-space.

With this we have already come into contact with the fourth determinant of the CO_2 absorption, the time factor. This is similarly a very important factor in the establishment of equilibrium between the dissolved CO_2 and that in the gas-space. That is, equilibrium is established in accordance with equation /3/ in a time process.

The time requirement for the establishment of equilibrium in a given case could be expressed by an artificial formula, but even today it cannot be correctly calculated in practice. The time requirement for the establishment of the equilibrium could be caldetermined only as the complex resultant of many factors which themselves are also variable, but in several cases the precise mathematical formulation of even these partial factors is not possible.

In the following only some of the determinants which have the most important effects on the time factor will be mentioned, simply to illustrate what has already been said.

The greater the contact surface between the solution and the gas-space, the faster the process. But the reaction is also accelerated by the increase of the temperature. The reaction time is likewise shortened if the gas-space is in turbulent motion. If there is also such a turbulen mixing motion in the solution space, this further increases the reaction rate. The qualitatively and quantitatively different absorption surfaces in the reaction space /e.g. mineral and organic soil particles/ either promote or hinder the absorption, depending on their specific properties.

The rate of the dissolution process will be different if the water is not in contact with limestone, than when there is such a contact and hence the formation of hydrocarbonate can begin simultaneously with the gas absorption. Many more such modifying factors could be listed.

It is undoubtedly true that this is one of the most complicated problems in the interpretation of the corrosion. Nevertheless, in spite of its complexity, at the same time it is one of the key questions in climatic karst morphogenetic analysis, and one of the fundamental modifying factors of the dynamism of limestone dissolution.

So far, the dissolution of the gaseous CO_2 has been studied only as regards the properties of the liquid and the gas phases, and the solid phase /in this case the limestone/ has not yet been considered. In the following we again return to the analysis of the combined steps of the dissolution process when all three phases are present simultaneously.

It is understandable that with the introduction of this new factor the equilibrium relations and interactions become even more extensive than when the binary system of only the water and the CO_2 gas was examined. The question is even more complex, because here it is no longer a matter only of simple dissolution or dissociation, but of the chemical transformations which are closely connected with the dissociation and other physical dissolution equilibria.

According to literature data /HOLLUTA 1927, PIA 1953/, at 4 °C 0.7 % of the absorbed carbon dioxide content of the solution is converted to carbonic acid, in agreement with the well-known classical equation:

$$CO_2 + H_2O \rightleftharpoons H_2CO_3 \qquad /4/$$

If it comes into contact with $CaCO_3$, the carbonic acid reacts with it, with the formation of calcium hydrocarbonate, and hence the limestone dissolves:

$$CaCO_3 + H_2CO_3 \rightleftharpoons Ca/HCO_3/_2 \qquad /5/$$

Naturally, the carbonic acid bound to the calcium and thus practically used up is replaced from the physically absorbed CO_2 of the solution /until this is exhausted/, so that in practice almost the entire amount of dissolved CO_2 takes part in the process of dissolving the limestone.

According to the calculations of TILLMANS and HEUBLEIN /TILLMANS 1932, 1940/, the lower the concentration of carbonic acid, the more effective is equation /5/ in the direction of the upper arrow. Thus, in weak solutions /e.g. a total dissolved CO_2 concentration of 10-15 mg/l the reaction proceeds almost completely according to the upper arrow, while in more concentrated solutions it does so only up to a certain fraction of the total absorbed CO_2. The reason for this is that in the case of higher ionic concentrations accessory or equilibrium free carbonic acid must be present in amounts gradually increasing with the concentration, so as to maintain the dissolved hydrocarbonate in equilibrium.

Figure 2 shows the most importantant bonding and equilibrium interactions governing the dissolution of $Ca/HCO_3/_2$.

<u>For every mg of CO_2 dissolved in the water, the solution can dissolve 2.2723 mg $CaCO_3$, independently of the temperature of the system</u>. Accordingly, therefore, at low concentrations, where it is still not practical to consider the equilibrium free carbonic acid requirements, from a knowledge of the amount of dissolved CO_2 the limestone dissolving capacity of the solution can be calculated at once. For example, the concentration of dissolved CO_2 in water saturated at 10 ^{o}C with air of normal composition /p CO_2 = = 0.0003/ is 0.70 mg/l. Without the entry of further gaseous CO_2 into the solution, this is capable of dissolving 2,2723 . 0.7 = 1.59 mg of limestone as hydrocarbonate.

Naturally, even under laboratory conditions such a limestone-containing solution can not occur in the presence of the solid phase, since the solid phase, since the solution is also bound to contain about 13 mg/l calcium carbonate as a result of the primary carbonate dissolution in accordance with equation /1/. It must also be pointed out that in addition to carbon dioxide oxygen too is absorbed in natural soil waters. This is used in bacterial and inorganic oxidation processes in the soil, and hence in the majority of cases gives rise to an increased CO_2 content /TUCAN 1933, CHRAMUSEV 1941, VENKOVITS 1949, STEFANOVITS 1956/.

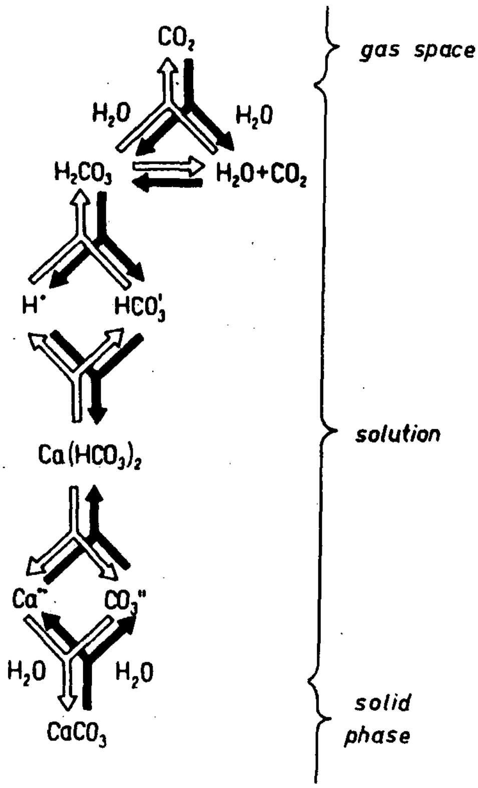

Figure 2. The most important chemical conditional components of the hydrocarbonate dissolution of limestone. The equilibrium shifts according to the black arrows and to the white arrows result in dissolution and precipitation of limestone, respectively. At the same time the equilibrium shift for the system can occur either only according to the black arrows, or only according to the white ones.

At higher concentrations the question of the dissolution is more involved only in so far as the total amount of carbon dioxide in the water can not be taken into account in the hydrocarbonate reaction, because the equilibrium free carbonic acid requirement must also be considered. It should be noted, however, that the amount of this accessory free carbonic acid now depends not only on the quantity of dissolved limestone, but also on the temperature of the environment.

In the presence of $CaCO_3$, therefore, the absorbed carbon dioxide is to be found simultaneously in the following forms in the aqueous solution:

1. In the form of <u>hydrocarbonate bound</u> to the the calcium.
2. In the form of <u>accessory, or equilibrium free carbonic acid</u> necessary to maintain the hydrocarbonate in solution.
3. In the form of <u>aggressive carbonic acid</u>, in amounts possibly exceeding the equilibrium requirements of the hydrocarbonate. This latter free carbonic acid obtained its name from its corrosion capacity, since not being involved in the existing solution equilibria, it can facilitate the dissolution of further limestone.

If the relative amounts of these three functional types of carbonic acid in a solution are known, it can be decided whethor the given solution is capable of further corrosion, whether the limestone and the carbonic acid are in equilibrium, or whether the solution is supersaturated and hence its tendency is to deposit calcium carbonate.

In the international chemical and hydrological literature, it was earlier possible to find the equilibrium free carbonic acid indexes only for waters at 17 °C /TILLMANS 1932, LAPTYEV 1939, TROMBE 1951, 1952, BÖGLI 1960, etc./. For this reason PAPP /1954, 1956/ calculated the accessory free carbonic acid contents of waters in limestone - carbonic acid equilibrium for all the more importantan concentrations and temperatures. The values most likely to be required in karst research work are given in Table 4.

It is also possible to decide from the Table the extents of the function of the temperature changes controlling the solubility, in so far as water possessing an unchanged total CO_2 content is capable of retaining less calcium carbonate in solution at higher temperatures, because at higher temperatures the amount of equilibrium free CO_2 necessary to keep the calcium hydrocarbonate in solution increases. If, for example, the total CO_2 content of a water in limestone - carbonic acid equilibrium at 5 °C is 957 mg/l /330 mg/l of this is bound CO_2, and 627 mg/l accessory carbonic acid/, this will keep in solution $Ca/HCO_3/_2$ corresponding to 749.7 mg/l solid $CaCO_3$. If the temperature of the water is now raised to 14 °C, however, with an unchanged total amount of carbonic acid, the limestone-dissolving capacity decreases, and thus the solution becomes supersaturated. In this case the 957 mg/l total CO_2 content now assumes a different distribution: the bound CO_2 will be 306.2 mg/l, and the equilibrium CO_2 650.8 mg/l, and accordingly the quantity of $CaCO_3$ which can be kept in solution by the water cannot be more than 969.1 mg/l. This means that 749.7 - 696.1 = 53.6 mg $CaCO_3$ must separate out from each litre.

Table 4

The bound and accessory CO_2-requirements of the hydrocarbonate dissolution of the limestone

$CaCO_3$ mg/l	bound CO_2	accessory CO_2 /mg/l/ at the following temperatures 5 °C	7 °C	9 °C	10 °C	11 °C	12 °C	15 °C	20 °C
8,92	3,85	-	-	-	-	-	-	-	-
17,85	7,70	-	-	-	-	-	0,01	0,01	0,01
26,77	11,5	0,03	0,03	0,04	0,04	0,04	0,04	0,04	0,05
35,70	15,6	0,07	0,07	0,07	0,08	0,08	0,08	0,09	0,00
44,52	19,4	0,14	0,15	0,16	0,17	0,17	0,18	0,19	0,23
53,55	23,5	0,23	0,24	0,26	0,26	0,27	0,28	0,30	0,35
62,47	27,3	0,38	0,41	0,44	0,45	0,46	0,48	0,51	0,59
71,40	31,5	0,54	0,58	0,61	0,63	0,65	0,67	0,73	0,84
80,32	35,3	0,79	0,84	0,89	0,92	0,95	0,97	1,06	1,23
89,25	39,2	1,06	1,11	1,18	1,21	1,25	1,28	1,40	1,62
98,17	43,0	1,39	1,52	1,61	1,65	1,71	1,75	1,91	2,21
107,1	47,1	1,82	1,93	2,04	2,10	2,17	2,23	2,43	2,81
116,0	50,9	2,27	2,50	2,65	2,79	2,81	2,89	3,15	3,64
124,8	55,0	2,90	3,08	3,26	3,36	3,45	3,56	3,88	4,48
133,8	58,8	3,60	3,82	4,04	4,16	4,28	4,41	4,81	5,56
142,8	62,7	4,30	4,56	4,83	4,97	5,12	5,27	5,57	6,64
151,7	66,5	5,22	5,53	5,86	6,03	6,21	6,40	7,48	8,06
160,6	70,6	6,14	6,51	6,90	7,10	7,31	7,53	8,21	9,49
169,6	74,4	7,29	7,73	8,19	8,43	8,70	8,96	9,75	11,2
178,5	78,5	8,45	8,96	9,49	9,77	10,1	10,4	11,3	13,1
187,4	82,5	9,92	10,4	11,0	11,3	11,7	12,1	13,2	15,2
196,3	86,5	11,4	11,9	12,7	13,0	13,4	13,8	15,1	17,4
205,3	90,4	13,0	13,6	14,5	14,9	15,3	15,8	17,3	19,9
214,2	94,2	14,6	15,4	16,4	16,8	17,3	17,8	19,5	22,5
223,1	98,1	16,6	17,5	18,6	19,1	19,7	20,2	22,1	25,6

$CaCO_3$ mg/l	bound CO_2	accessory CO_2 /mg/l/ at the following temperatures							
		5 °C	7 °C	9 °C	10 °C	11 °C	12 °C	15 °C	20 °C
232,0	102,1	18,6	19,7	20,8	21,5	22,1	22,7	24,6	28,7
241,0	106,0	20,9	22,1	23,4	24,1	24,8	25,5	27,9	32,3
249,9	110,0	23,2	24,6	26,1	26,8	27,6	28,4	31,0	35,9
258,8	113,9	25,9	27,4	29,1	29,9	30,3	31,7	34,6	40,0
267,7	117,9	28,6	30,3	32,1	33,0	34,0	35,0	38,2	44,2
276,7	121,8	31,6	33,4	35,4	36,5	37,5	38,6	42,2	48,8
285,6	125,6	34,6	36,6	38,8	40,0	41,1	42,3	46,2	53,4
294,5	129,5	38,0	40,3	42,7	44,0	45,2	46,5	50,3	58,7
303,3	133,5	41,5	44,0	46,6	48,0	49,4	50,8	55,5	64,1
312,3	137,4	45,4	48,1	51,0	52,5	54,0	55,6	60,7	70,1
321,3	141,4	49,3	52,3	55,4	57,0	58,7	60,4	65,9	76,2
330,2	145,3	53,5	56,8	60,1	61,9	63,7	65,6	71,6	82,8
339,1	149,2	57,8	61,3	64,9	66,8	68,8	70,8	77,3	89,4
348,0	153,1	62,6	66,4	70,3	72,4	74,5	76,7	83,7	96,9
357,0	157,1	67,5	71,5	75,8	78,0	80,3	82,7	90,2	104,3
365,9	161,0	72,9	77,2	81,9	84,3	86,7	89,3	97,5	112,7
374,8	165,0	78,4	83,0	88,0	90,6	92,3	96,0	104,8	121,1
383,8	168,9	84,3	89,2	94,6	97,4	100,2	103,2	112,6	130,2
392,7	173,5	90,2	95,5	101,3	104,3	107,3	110,5	120,5	139,3
401,6	176,9	96,5	102,2	108,3	112,5	114,8	118,2	128,9	149,0
410,5	180,7	102,8	108,9	115,4	118,8	122,3	125,9	137,4	158,8
419,5	184,6	109,8	116,3	123,3	126,9	130,7	134,5	146,8	169,7
428,4	188,5	116,8	123,8	131,2	135,1	139,1	143,2	156,2	180,6
437,3	192,4	124,5	131,9	139,8	143,9	148,2	152,5	166,8	192,4
446,2	196,4	132,2	140,1	148,4	152,8	157,3	161,9	176,6	204,2
455,2	200,3	140,3	148,7	157,6	162,2	167,0	171,9	187,5	216,8
464,1	204,2	188,5	157,4	166,8	171,7	176,8	182,0	198,5	229,5
473,0	208,1	159,0	166,9	166,8	182,0	187,4	192,9	210,5	243,3

$CaCO_3$ mg/1	bound CO_2	accessory CO_2 /mg/1/ at the following temperatures							
		5 °C	7 °C	9 °C	10 °C	11 °C	12 °C	15 °C	20 °C
481,9	122,1	166,5	176,4	186,9	192,4	198,1	203,9	222,5	257,2
490,8	216,0	176,1	186,6	197,7	203,6	209,6	215,7	235,4	272,1
499,8	220,0	185,7	196,8	208,6	214,8	221,1	227,6	248,3	287,0
508,7	223,9	196,1	207,8	220,2	226,7	233,4	240,3	262,1	303,0
517,6	227,9	206,5	218,8	231,9	238,7	245,8	253,0	276,0	319,1
526,5	231,8	217,3	229,8	244,0	251,2	258,6	266,2	290,4	335,8
535,5	235,7	228,1	241,8	256,2	263,8	271,5	279,5	304,9	352,5
553,4	243,5	251,9	266,9	282,9	291,2	299,8	307,9	336,6	389,2
571,2	251,2	276,5	293,0	310,5	319,6	329,1	338,0	369,5	427,2
589,0	259,2	303,3	321,5	340,7	350,7	361,0	370,8	405,4	468,7
606,9	267,1	331,9	351,8	372,8	383,8	395,1	405,8	443,6	512,9
624,7	275,0	362,8	384,5	407,5	419,5	431,5	443,5	484,9	560,6
642,6	282,7	394,1	417,6	442,5	455,6	469,0	481,7	526,6	608,8
660,3	290,6	428,1	453,6	480,7	494,9	509,5	523,3	572,1	661,4
678,3	298,5	464,0	491,7	521,1	536,5	552,3	567,2	620,1	716,9
696,1	306,2	500,8	530,7	562,5	579,0	596,1	602,2	669,3	773,8
714,0	314,1	540,6	572,9	607,1	625,0	643,4	660,9	722,5	835,3
731,8	322,0	582,5	617,3	654,1	673,4	693,3	712,0	778,5	900,0
749,7	330,0	327,0	664,4	704,1	724,8	746,2	766,4	837,9	968,7
767,5	337,7	671,8	711,9	754,5	776,7	799,6	821,2	897,8	1038
785,4	345,6	720,1	763,1	808,7	832,9	857,1	880,3	962,4	1112
803,2	353,6	770,5	816,6	865,3	890,8	917,1	941,9	1029	1190
821,1	361,2	822,0	871,1	923,2	950,3	978,4	1004	1098	1271
838,8	369,1	877,1	929,5	985,1	1014	1044	1072	1172	1355
856,8	377,0	934,7	990,5	1049	1080	1012	1142	1249	1444
874,6	385,0	995,6	1055	1118	1151	1185	1217	1330	1538
892,5	392,7	1056	1119	1186	1221	1257	1291	1411	1632

The above relations can be illustrated in the form of a complex graph /Fig. 3/ derived from the values given in Table 4. The abscissa of this diagram shows the total amount of CO_2 in the solution, and the ordinate the amount of $CaCO_3$ dissolved, both in mg/l. If the previously determined total CO_2 content or dissolved $CaCO_3$ content is projected into the system, the chemical nature of the water studied can readily be read off.

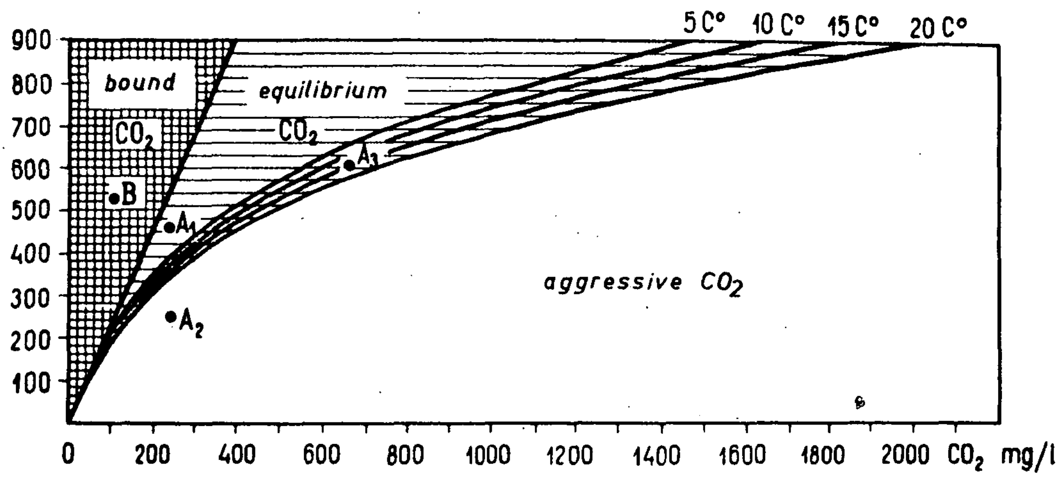

Figure 3. Amounts of bound carbonic acid and equilibrium free carbonic acid in waters in limestone - carbonic acid equilibrium at 5, 10, 15 and 20 °C.

If, for instance, the total amount of CO_2 is 250 mg/l, and the amount of dissolved $CaCO_3$ is 450 mg/l /in this case the point A_1 denotes the state of the water on the diagram/, it can be seen at once that the water is strongly supersaturated, and thus $CaCO_3$ will precipitate from it. If, on the other hand, the amount of dissolved $CaCO_3$ in only 250 mg/l, then the water is strongly aggressive, because this state /position A_2 on the diagram/ is in a region of unsaturation. At the same time, another water, defined on the basis of analysis by point A_3, and obviously at equilibrium at 12 ^{o}C, becomes aggressive if cooled to a temperature lower than this, and supersaturated at higher temperatures.

Of course, it is not possible to find a water sample which can be denoted by a point inside the region of bound CO_2 /e.g. B/.

It must be mentioned here that the aggressivity of a water does not lead to the immediate unfailing dissolution of limestone in all cases, for if it is possible for the carbon dioxide to evaporate out of the solution, then this in an alternative method for equilibrium corresponding to the new conditions to be established.

The route by which the system strives to attain equilibrium in a given case depends on many involved factors. In a closed system where there is no possibility for the evaporation of CO_2 into the gas-space, the equilibrium can only be restored by the increase of the corrosion. /This is why waters circulating in a closed network of tubes are so corrosion-dangerous, even if they are only slightly aggressive./

The aggressivity of water can readily be calculated numerically from a knowledge of the total CO_2 content and the carbonate hardness* from Table 4.

By the combined use of Table 3 and 4, still further very significant considerations are possible as regards karst research. Thus, from a knowledge of the p CO_2 values of the soil atmosphere determining the chemical nature of the water in the infiltration zone, the extent of limestone transportation can be calculated.

Let us now consider a concrete example of the use of these Tables for such calculations:

The water has been acted on in the soil by air with a partial pressure of 8/100, and the water - carbonic acid equilibrium has been established by contact with a gas-space of this concentration. The temperature of the soil during the infiltration period was 5 °C. In this case the water has a total carbonic acid content of 224 mg/l /see Table 3/. The aggressive water dissolves up limestone in its network of crevices, and during the seepage downwards a limestone

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* The carbonate hardness of the water id determined by the sum of the calcium and magnesium hydrocarbonates dissolved in it. One German hardness degree means 10 mg/l CaO, or 17.85 mg/l $CaCO_3$. Thus, for example, water with a German hardness degree of 22, if the hardness is caused only by calcium salts, contains $17.85 \cdot 22 = 392.7$ mg/l of $CaCO_3$ dissolved as hydrocarbonate.

- carbonic acid equilibrium is established. The amount of dissolved limestone is found from Table 4; this is done by seeing how the total CO_2 content of 224 mg/l is divided at 5 °C between bound and equilibrium free carbonic acid. Values of these are sought such that their sum corresponds as closely as possible to 224 mg/l. In this case the sum of 157.1 mg/l bound carbonic acid and the related 67.5 mg/l accessory CO_2 approximates well to the desired number, the difference being negligible. It only remains to read off the value of $CaCO_3$ in mg/l from the first column of Table 4, giving in the present case a figure of 357.0 mg/l.

From this, however, we have so far found only the amount of limestone which may be dissolved by the karst water under favourable conditions. As to how much may be reprecipitated from the solution under given conditions, such as those in a cavern, this can be learnt only from further calculations.

If, for instance, the karst water in question finds its way into a cavity in a cavern at 10 °C where the partial pressure of CO_2 in the air is 2/100, then if a suitable amount of time is available a new equilibrium state will develop corresponding to the CO_2 content of the new atmosphere; this means, according to Table 3, that the total CO_2 content of the solution will be 46.9 mg/l /the rest evaporates/. Next, by the already known method, the $CaCO_3$ value must be found from Table 4 corresponding to

/bound CO_2/ + /equilibrium CO_2 at 10 °C/ = 46.9 mg/l

Concretely, it is seen that under the new equilibrium conditions the solution contains only about 100 mg/l $CaCO_3$. The difference in the two values /357 - 100 = 257 mg/l/ is thus the desired amount which is transported by the water from one point of the karst to another.

It must be noted here, however, that although a good approximation may often be obtained, nevertheless these calculations can not always be regarded as entirely realistic. The problem is that in nature there are several factors which cannot always be calculated at present, e.g. the time factor, the other gases dissolved in the water /mainly oxygen/, the modifying actions of the humus and root acids in the zone of decomposition of the organic matter, etc. These vary from case to case, and at times may make such a significant contribution that they can change the quantity of limestone dissolved considerably.

From another aspect, it also emerges from Table 4 that while the amounts of CO_2 bound as hydrocarbonate increase linearly with the amount of dissolved $CaCO_3$, the increase of the equilibrium free carbonic acid is of a progressive nature; that is, the successively increased amount of dissolved $CaCO_3$ can be kept in an equilibrium state only by the ensurance of continually more rapidly increasing amounts of accessory free carbonic acid. The relation is expressed by the following formula, due to TILLMAS:

$$\text{equilibrium } CO_2 = \frac{/\text{bound } CO_2/^3}{K_t} \qquad /6/$$

where the factor K_t is a constant for a given temperature.

It follows clearly from all this that during the mixing of equilibrium hydrocarbonate solutions of different concentrations /e.g. natural soil and karst waters/ carbon dioxide will become surplus in the solution, that is the solution will become aggressive. Depending on the conditions, this carbonic acid excess will evaporate from the solution, or may lead to the dissolution of more $CaCO_3$. In such a way, a secondary dissolution process can come about; this is known as mixing corrosion. LAPTYEV /1939/ was the first to draw attention to its existence, but its role in karstification has been suitably stressed only by BÖGLI /1963/, and in Hungary by ERNST /1964/ and BALÁZS /1966/.

The extent of the reaggressivity appearing on mixing the solutions is the greater, the larger the difference in the initial hydrocarbonate concentrations of the mixed equilibrium solution components. Only a minor role is played in this question by the temperature factor.

Let us now confirm the above findings by the examination of some concrete data from Table 4.

Before mixing, the equilibrium solutions A and B had the following compositions:

solution A /9 °C/	$CaCO_3$ content dissolved as hydrocarbonate	151.7 mg/l
	bound CO_2 content	66.5 mg/l
	equilibrium free CO_2 content	5.8 mg/l

solution B /9 °C/		
	$CaCO_3$ content dissolved as hydrocarbonate	508.7 mg/l
	bound CO_2 content	223.9 mg/l
	equilibrium free CO_2 content	220.2 mg/l

If it is assumed that /for the sake of simplicity/ equal volumes of A and B are mixed, then the product, solution C, will have the following composition:

solution C /9 °C/		
	$CaCO_3$ content dissolved as hydrocarbonate	$= \frac{151.7 + 508.7}{2} = 330.2$ mg/l
	bound CO_2 content	$= \frac{66.5 + 223.9}{2} = 145.2$ mg/l
	free CO_2 content	$= \frac{5.8 + 220.2}{2} = 113.0$ mg/l

If the adequate carbonic acid values related to the dissolved $CaCO_3$ content of solution C, 330.2 mg/l, are looked for in Table 4, it is seen that the value for the bound carbonic acid is in agreement, whereas at 9 °C the requirement of solution C for accessory free carbonic acid is equivalent to only 60.1 mg/l CO_2. Thus, as a result of the mixing there will be a 113.0 - 60.1 = 62.9 mg/l excess of in statu nascendi CO_2 in solution C, which means that the solution now contains aggressive carbonic acid.

Using the same method as in the above example, we have calculated the concentrations of the aggressive carbonic acid adequate CO_2 released on mixing equal quantities of waters with carbonate hardnesses of 0-50, at 10 °C. The results are shown in Table 5.

Table 5

Hardness German degrees	0°	5°	10°	15°	20°	25°	30°	35°	40°	45°	50°
0°	0										
5°	0,5	0									
10°	3,7	1,3	0								
15°	12,4	7,3	2,4	0							
20°	29,2	20,6	10,8	3,1	0						
25°	57,4	43,9	28,8	14,9	2,7	0					
30°	98,8	80,0	58,8	35,8	18,1	4,7	0				
35°	157	132	102	73,5	45,2	22,3	6,0	0			
40°	234	200	164	126	87,6	64,1	24,8	5,8	0		
45°	333	293	247	198	149	102	61,4	30,3	7,7	0	
50°	448	407	351	292	230	169	117	70,1	32,4	7,8	0

Amounts of aggressive carbonic acid CO_2 /mg/l/ formed on the 1:1 mixing of equilibrium waters at 10 °C with German hardness factors of 0-50

The same data are also plotted graphically in Figure 4. Hence, by means of the continuity of the lines on the diagram the amounts of in statu nascendi CO_2 relating to the intermediate values can be read off directly.

It has been mentioned that temperature changes act in a subordinate way, and only as a modifying factor, in the quantitative control of the aggressive carbonic acid formed on mixing. To illustrate this, let the temperature of solution. A in the above example now be 9 °C still, but that of solution B 15 °C. After mixing, the temperature of solution C will then be 12 °C.

In accordance with the new temperature, the equilibrium amount of CO_2 in solution B is now 262.1 mg/l compared with the previous 220.2 mg/l. The other characteristics of solutions A and B do not change. Thus, the total quantity of free CO_2 in solution C can be calculated as:

$$\frac{5.86 + 262.1}{2} = 133.9 \text{ mg/l}$$

Since the equilibrium carbonic acid requirement of solution C at 12 °C is 65.6 mg/l, then as a result of the mixing there will be a free CO_2 excess of 133.9 - 65.6 = = 68.3 mg/l. This is only 5.4 mg/l more than the amount released on mixing the solutions which were both at 9 °C.

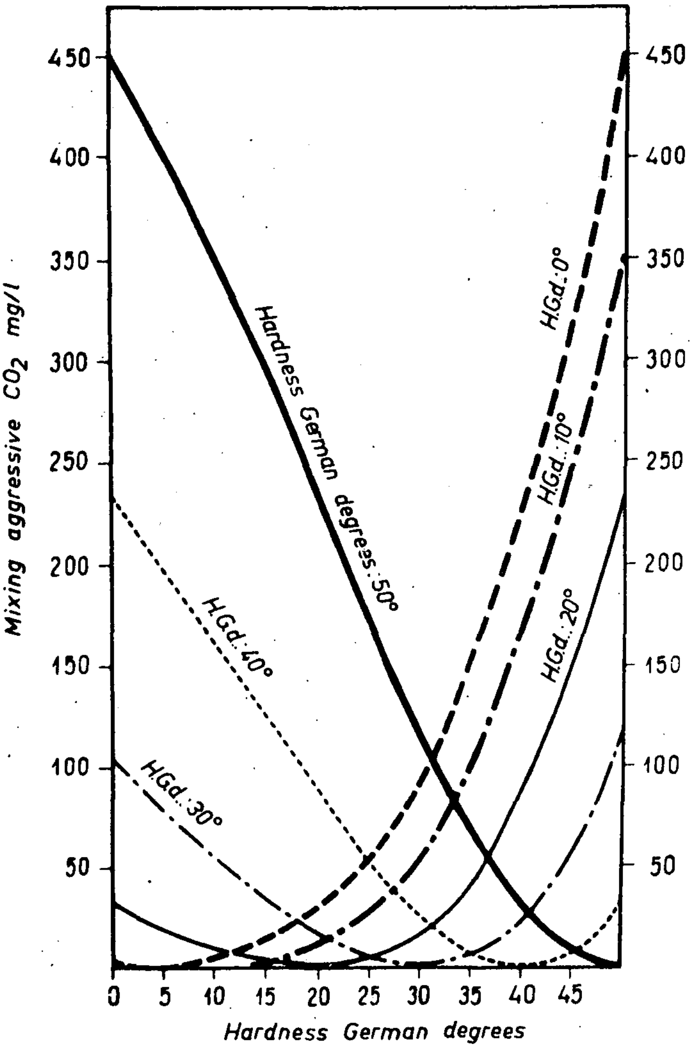

Figure 4. Amounts of aggressive carbonic acid /CO_2 mg/l/ formed in the 1:1 mixing of karst waters of various hardnesses at 10 °C.

It can be stated that <u>the larger the temperature difference between the two solutions to be mixed, the greater the amount of aggressive CO_2 formed</u>. For example, if the temperature of solution A is only 5 °C, while that of solution B is 15 °C, it can readily be calculated that 60.7 mg/l aggressive CO_2 will be produced in the solution C formed with a temperature of 10 °C. This is 7.8 mg/l more than the amount formed on mixing solutions A and B, both at 9 °C.

The diagrams of Figure 5 were plotted from the results of calculations in this connection. They show the amounts of in statu nascendi CO_2 released on the mixing of equal volumes of soft water not containing dissolved chemicals /pure rain-water/ and equilibrium karst waters of various carbonate hardnesses. The calculations were performed for systems at 5, 10 and 20 °C.

Of course, only part of the unbound carbonic acid released during the mixing processes in able to dissolve further $CaCO_3$, for the remainder is required to keep the newly dissolved amount in equilibrium.

The very important question from the point of view of the karst researcher, as to how much limestone can be dissolved by secondary dissolution as a result of the aggressive CO_2 released when solutions mix, can be answered most simply in the following way with the use of Table 4:

The concentrations of all the bound and accessory CO_2 in the equilibrium solutions A and B are added together, and the result divided by two. The value so obtained is the total amount of CO_2 in one litre of solution C. The bound CO_2 values and the accessory CO_2 values at the

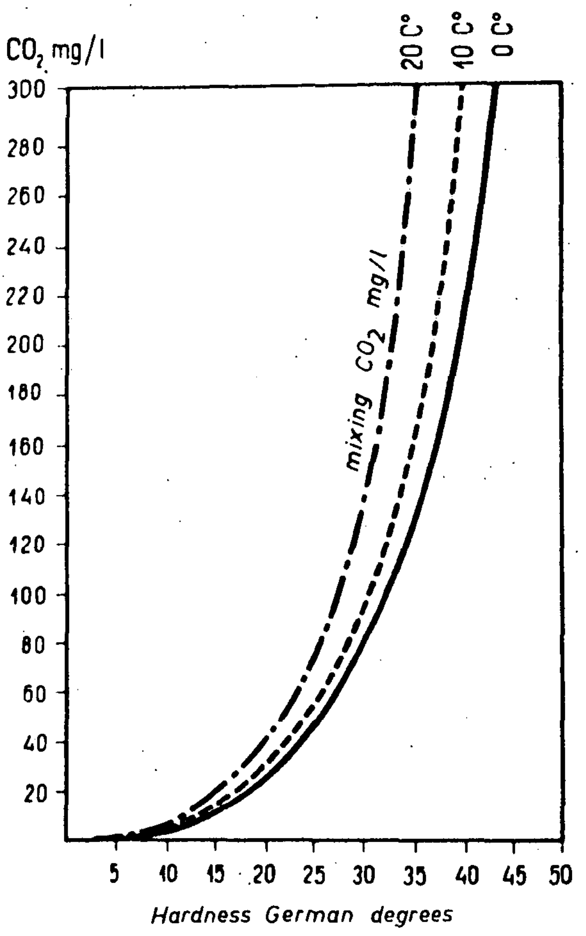

Figure 5. Amounts of in statu nascendi CO_2 /mg/l/ released on the 1:1 mixing of soft water not containing dissolved chemicals and equilibrium waters of various carbonate hardnesses in systems at 5, 10 and 20 °C.

appropriate temperature are taken from the columns of the Table and added together. This is done until the sum is the same as the already calculated total CO_2 concentration. The sought-for amount of secondarily dissolved limestone is given by the difference between the $CaCO_3$ value relating to the row giving the coincidence, and the average $CaCO_3$ value for solution C.

Let us now illustrate the above on the example of solutions A and B at 9 °C.

The total CO_2 supply of solution C, obtained by summing the concentrations in solutions A and B, and averaging, is:

$$\frac{66.5 + 5.8 + 223.9 + 220.2}{2} = 258.2 \text{ mg/l.}$$

The average $CaCO_3$ supply in this same solution C has already been calculated: 330.2 mg/l.

If the sums of the bound CO_2 value and the accessory CO_2 value at 9 °C, as obtained from the relevant columns of the Table, are compared with the total CO_2 content of 258.2 mg/l, with a little interpolation it can readily be found that, in an equilibrium state, this corresponds to 166.7 mg/l bound CO_2 and 91.5 mg/l accessory CO_2.

Next, the amount of $CaCO_3$ actually dissolved by solution C can easily be calculated from the formula N.V, where N = the concentration of bound CO_2 in the solution /mg/l/, and V = 2.2723, a constant.

In this case, therefore, in its new equilibrium state solution C will be capable of retaining in solution an amount of hydrocarbonate equivalent to 166.8 . 2.2723 = 378.8 mg/l $CaCO_3$. Thus, by means of the mixing corrosion the solution is capable of the secondary dissolution of 378.8 - 330.2 = = 48.0 mg/l limestone.

Contradictory views can be found in the literature as regards the role of the mixing corrosion in karstification. According to BÖGLI, one of the leading authorities in this question, /BÖGLI 1963a, 1963b/, it is important only in those zones deep in the karst where the passages are completely filled with water and there are no well-ventilated air--spaces into which the released aggressive carbonic acid might evaporate. In contrast with this, it has been pointed out by Hungarian research workers among others /GÁNTI 1957, MAUCHA 1960, CZÁJLIK 1962, ERNST 1964/, and supported by numerous observations and analyses, that the recent corrosion of cave waters appearing to be strongly supersaturated may frequently be **observed** even in wide passages.

It is clear that the debate can be settled by the study of the rates of the dissolution and gas-diffusion processes, and in this respect we consider that the opinions of FRANKE /1965/, ERNST /1964/ and BALÁZS /1966/ most closely reflect the truth. They hold the view that mixing karst waters of different hardnesses may become capable of dissolution even when in contact with a free air-space. The evaporation of carbon dioxide from the solution takes place only at the surface of contact of the two media, and is therefore a slow process, whereas the rate of mixing of the water components is much higher since they are in turbulent motion, and so the water molecules in contact with the rock surfaces are continually being replaced by fresh ones.

It is correctly stressed by BALÁZS /op. cit. p. 184/ that: "The greatest concentration differences in the waters of our karst caves may appear when the very hard karst waters originating from infiltration and stagnating in the depths, are mixed with the alluvial waters from melting snow or sudden summer storms." In his view, on each such occasion the inrushing waters may permit the secondary dissolution of several hundred kilograms of limestone in the larger Hungarian caves, quite apart from their possible inherent aggressive effects.

As regards the many details of the question and the extent of the dissolution under natural conditions, of course, a final answer can be expected only after the collection and evaluation of many more careful observations. Nevertheless, it can already be stated with certainty that the mixing corrosion, as one of the important components of the hydrocarbonate dissolution process, plays a really factorial role in the development of the karsts.

We have so far made a multilateral analysis of the multicomponent regularities of the interactions governing the amount of carbon dioxide in the atmosphere, the carbonic acid content of the water, and the amount of limestone dissolved by the solution. It still remains to introduce a very important equilibrium relation which must be assumed between the partial pressure of CO_2 in the atmosphere /or soil atmosphere/ and the solution in limestone - carbonic acid equilibrium. This is at the same time the most refined and the most time-requiring equilibrium of the hydrocarbonate dissolution. This is why in many cases under natural conditions the karst water does not attain equilibrium.

Here, therefore, the amount of dissolved carbonic acid consumed during the hydrocarbonate formation process will show up as a loss in the equilibrium balance for the first-degree binary system atmophere - water, and this results in a renewed tendency for the dissolution of atmospheric carbon dioxide. Thus, in other words it could be said that since the amounts of carbonic acid bound to calcium /or magnesium/ as hydrocarbonate are no longer involved in the absorption equilibrium, and only the accessory CO_2 is in an equilibrium relation with it /according to equation /6//, then the accessory carbonic acid in the solution must come into a new adequate equilibrium relation with the partial pressure of CO_2 in the air /according to equation /3//. That is, as shown by Figure 2 the progress of the limestone-dissolving process produces effects all the way back to the atmosphere in contact with the solution, and leads to the absorption of further carbon dioxide from this.

In this way, the water in contact with a limestone will continue to absorb carbon dioxide from the atmosphere until equilibrium according to equation /3/ has been established between the atmospheric CO_2 and the accessory /equilibrium/ free carbonic acid of the solution. This does not mean, therefore, that the SCHLOESING Table /Table 3/ is unusable, but simply leads to the limitation that in the case of a dissolved limestone content the values of the Table must be referred to the equilibrium CO_2 values of Table 4 at the appropriate temperature.

Let us now consider the above in the case of an earlier used example.

In an equilibrium state at 5 °C, the partial pressure of CO_2 in ordinary atmospheric air, 0.0003, corresponds to 0.84 mg/l dissolved CO_2. We have already seen that if this carbonic acid value is regarded as stationary, then the hydrocarbonate-dissolving capacity of saturaturated water in air is very slight. If, however, in accordance with the extent of its exhaustion in the hydrocarbonate dissolution, the means and the time are available for further absorption from the atmosphere, by the time this dissolved CO_2 value of 0.84 mg/l is again established as the accessory carbonic acid in equilibrium with the hydrocarbonate, the water has already dissolved up about 81.97 mg/l $CaCO_3$ /calculated by interpolation from Table 4/.

Thus, it becomes quite understandable that even the softest karst waters, which are typical of completely bare karsts and alpine, snow-zone karsts, may contain as much as 80-100 mg dissolved limestone per litre. /BALÁZS /1963 reports a value of only 104 mg/l for the limestone content of the Cadisha spring which emerges from the bare karstic mass of the 3000 m high Kornet es Saouda in the Lebanon. The Lodowe Zródlo karst spring which surfaces in the Polish West Tátra contains 75-85 mg/l $CaCO_3$. KESSLER determined

80-100 mg/l $CaCO_3$ in karst waters originating from the depths of bare Albanian karsts at a plateau height of 2000 m . BAUER /1964/ and TELL /1961/ mention karst waters of similarly low concentrations in the Austrian Alps and in Sweden, respectively./

As regards order, the above values agree quite well with the results of theoretical calculations obtained by other means /MILLER 1952, MÁNDY 1954, GÁNTI 1957, ERNST 1961, MARKÓ 1961, FRANKE 1967/.

The question of the time requirements of the series of hydrocarbonate limestone dissolving reactions/ has been dealt with recently by BÖGLI /1960, 1963/. He found that as regards the time requirements of the hydrocarbonate dissolution of limestone it is convenient ot divide the dissolution into four stages as follows.

In the first stage, which is very rapid, the simple physical dissolution of the $CaCO_3$ occurs as in equation /1/. The partial conversion of the CO_2 absorbed by the water to give carbonic acid, and the dissociation of this to H^+ and HCO_3^- ions has already occurred earlier. The time needed for the first stage is about 1 sec.

The second stage, during which the carbonate ions /CO_3^{2-}/ of the limestone become bonded to the H^+ ions of the carbonic acid, can not be distinguished in time from the first. Because of the loss of CO_3^{2-} ions, however, the equilibrium which develops in the first stage is disrupted in this one, and this means that further physical /carbonate/ dissolution of the limestone must of necessity follow.

In the second stage, however, the equilibrium of the physically and chemically dissolved CO_2 in the water is also disturbed. Because of this the third stage soon begins. This is the transformation of the physically dissolved carbon dioxide to carbonic acid.

BÖGLI found the time requirements of this third stage to be about 1 minute. During this time the original CO_2 supply of the water is used for the hydrocarbonate dissolution of the limestone. According to him the fourth stage then begins: further amounts of carbon dioxide are absorbed from the atmosphere. By this means the series of dissolution reactions continues until the final equilibrium state has developed. This is defined by an equilibrium of the highest order via the repeated transfer of the amounts of limestone dissolved as hydrocarbonate and the carbon dioxide content of the atmosphere in contact with the water.

In this way, the dynamics of the dissolution of the limestone in the fourth stage are determined by the rate of absorption of gaseous carbon dioxide, and this is very low. According to BÖGLI, 24-60 hours is required for the establishment of the final equilibrium. FREAR and JOHNSTON, on the other hand, mention several days.

A very important factor involved in the determination of the absorption and diffusion rates is the <u>temperature</u>. When this is low it substantially slows down the gas absorption, but when it is high the absorption can be accelerated many times /because of the more rapid motion of the molecules colliding on the surface between the media, and hence because of their higher number/. According to the generally accepted view of FEITKNECHT, for every temperature increase in the solution of 10 °C the rate of reaction is approximately doubled. The duration of the absorption and /for the motion of the process in the opposite sense/ diffusion is also significantly affected by the size of the surface per unit amount of water. Accordingly, the greater the exchange surface /water drops, aerosol, waterfall, etc./, the greater the material transport in a given unit time. The extent of the material transport in unit time, however, is also influenced considerably by the hydrostatic pressure, as was shown above.

The modern analytical results of GERSTENHAUER and PFEFFER /1966/ are in contradiction with the theory of BÖGLI regarding the duration of the dissolution; in particular they cast strong doubt /and rightly so in our view/ on the reaction rates of BÖGLI's stages 1, 2 and 3. Thus, if we accept BÖGLI's breakdown of the series of reactions into four stages, because of the didactic viewpoints of its descriptiveness, we must know that in practice the individual stages never follow one after the other. They always come about simultaneously and mutually, that is they are not separated into discrete stages. The reversibility chain of the series of dissolution reactions, with the narrowest permeable capacity during unit time, in fact takes place according to the uppermost arrow shown in Figure 2, that is between the water and the atmosphere. But in our view for just this reason it is more correct to formulate the problem so that the rate of hydrocarbonate dissolution in the three-component system is determined fundamentally from the beginning on by this absorption or diffusion material transport capacity. The factorial components and comprehensive regulating conditions of this, however, have already been studied in detail earlier.

III. Non-karstic corrosion of limestone

While the simple physical /carbonate/ and carbonic acid /hydrocarbonate/ processes of dissolution of limestone are collectively termed karstic corrosion, the corrosive denudative processes connected with the other chemical effects form the non-karstic group of the chemical weathering of limestone.

In this respect very many, mainly double decomposition chemical reactions may be given, primarily consisting of the mutual reactions of the limestone and the chemically active constituents of the soils of various compositions. These are in part predominantly the effects of the chemical products formed by means of inorganic mineralization weathering processes in the soil; in part the organic and inorganic chemical products /mainly various acids/ of plant and animal refuse decomposing under aerobic or anaerobic conditions in the humus levels of the soils, and selected by soil microorganisms and the roots of plants living in the soils. On the action of all such soil processes which from our point of view can be generally regarded as non-karstic corrosive factors, calcium from the limestone gives up its carbonate bonding and a completely new calcium compound is formed. This is either transported away in the form of its solution, or it remains for a longer or shorter time in an autochthonous state as a solid reaction product.

The up-to-date pedological, agrochemical and soil-biological handbooks /FEKETE 1952, 1958, STEFANOVITS 1959, 1963, FEHÉR 1954, PEJVE 1961, DI GLÉRIA 1962, BALLENEGGER and DI GLÉRIA 1963, FEKETE, HARGITAI and ZSOLDOS 1964, BECK 1968/ give a detailed analysis of humification processes whose dynamics are greatly affected by the climatic conditions, and which are characteristic of soil-levels and of soils of various compositions. Of the dissimilation compounds formed during the aerobic decomposition of organic substances in the soil, or as a result of the life-functions of the microorganisms in the soil, those which are the most important form the point of view of the corrosion of the limestone are formic acid, oxalic acid, acetic acid, propionic acid, lactic acid, the various root secretions, and of course the already discussed carbonic acid. These all form the corresponding calcium salt with the limestone.

It would still be difficult today to decide the extents of the separate individual dynamics of these compounds in the dissolution of limestone, all the more so because their effects in the soil are complex and simultaneous, and because the proportion of their regional contribution in the soil solution is not constant either. Their overall effect, however, is more easy to establish. It is sufficient for the demonstration of this for us to point to one of the most classical experiments of biochemistry. In this a seed was caused to germinate on a marble surface; during even a short time the minute root of the seed left a clearly visible trace on the smooth surface of the $CaCO_3$ /SACHS 1865/.

The most important of the corrosive organic acids formed during the aerobic decomposition processes /under anaerobic conditions too, but much more slowly/ are the fulvic and crenic acids. In an acidic soil medium /under aerobic conditions/ these exert particularly active dissolving effects, and their resulting salts remain in solution.

Limestone is also actively corroded by the humous and humic acids of the soil, but in acidic medium the calcium salts of these are precipitated.

The effects of inorganic acids and salts formed in the course of biogenetic or mineral weathering processes in the soil are also of great importance from the point of view of the corrosion denudation of the limestone. Of these, sulphuric and nitric acids among others, as very strong acids, even in very low concentrations give rise to the fact that their double decompositions with limestone are unidirectional /irreversible/:

$$CaCO_3 + H_2SO_4 \longrightarrow CaSO_4 + H_2O + CO_2 \qquad /7/$$

$$CaCO_3 + 2\ HNO_3 \longrightarrow Ca/NO_3/_2 + H_2O + CO_2 \qquad /8/$$

It should be noted that the formation of the above acids in the soil may be connected with various processes. Thus, the sulphuric acid most frequently originates from the inorganic or biogenic /activity of sulphur bacteria/ oxidation of sulphides /e.g. pyrite/ and hydrogen sulphide /H_2S/. The starting compounds are formed from the chemical weathering of inorganic constituents of the soil, and more frequently from the mainly anaerobic process of decomposition of the organic refuse derived from living organisms. FEHÉR /1954/ reports that, for example, it is typical of the functioning of <u>Achromatium</u>, <u>Beggiatoa</u>, <u>Thiotrix</u>, <u>Thioploca</u>, and other genera belonging to the <u>colourless sulphur bacteria</u>, that they first split off sulphur from the H_2S released in the decomposition of proteins. This is stored in the form of drops in their plasma, and gradually consumed so that energy is obtained for their C-assimulation.

In outline, the process is as follows:

$$\begin{aligned} 2\,H_2S + O_2 &\longrightarrow 2\,H_2O + 2\,S \\ 2\,S + 3\,O_2 + 2\,H_2O &\longrightarrow 2\,H_2SO_4 \quad /+244\ \text{Cal}/ \end{aligned} \qquad /9/$$

According to FEHÉR /op. cit. p. 115/, the life-function of the hydrogen sulphide-oxidizing <u>purple bacteria</u> proceeds via a process which is somewhat more complex than the previous one. These are also aerobic organisms, and thus they oxidize hydrogen sulphide and assimilate chemosynthetically. With the intervention of bacteriochlorophyll and bacterioerythrin in their plasma, they are also able to use the photoenergy of the sun, and so they carry out photosynthetic assimilation at the same time too. With the help of the hydrogen sulphide, and with the use of photoenergy, the CO_2 is deoxygenated and hydrogenated to give formaldehyde:

$$H_2S + 2\,H_2O + 2\,CO_2 \longrightarrow 2\,HCHO + H_2SO_4 \qquad /10/$$

Of the sulphur bacteria living in the soil, <u>Thiocystis</u>, <u>Thiospirillum</u>, <u>Rhabdomonas</u>, <u>Rhodothece</u>, and other genera can be classified in this group.

Ammonia, resulting likewise mainly from organic decomposition, must be regarded as the most probable starting substance for the formation of nitric acid in the soil. With the intervention of bacteria, the ammonia is oxidized in the soil to acids which have a corrosive action on limestone. It was already demonstrated in the last century by VINOGRADSKII /1892/ that the process of nitrification in the soil is carried out by two metabiotically cooperating groups of bacteria: the nitrite-forming and the nitrate-forming bacteria. The nitrite bacteria oxidize the ammonia to nitrous acid, and the nitrate-forming bacteria oxidize the nitrous acid so formed to nitric acid:

$$2\,NH_3 + 3\,O_2 \longrightarrow 2\,HNO_2 + 2\,H_2O \quad /+156.6\ \text{Cal}/ \quad /11/$$

$$2\,HNO_2 + O_2 \longrightarrow 2\,HNO_3 \quad /+43.6\ \text{Cal}/ \quad /12/$$

Of course, neither the nitrous acid nor the nitric acid can remain in the soil in an unbound state, and immediately on their formation react with the cations of the soil and the limestone to form their nitrites or nitrates /equation /8//.

It should be noted that a certain amount of nitric acid can enter the soil from the atmosphere. As stressed by FINDEISEN /1939/, HARRASOWITZ /1954/, KILINSKI /1958/ and REITER /1960/, the summer rain almost always contains nitric acid. This is formed in the atmosphere by the electric discharges accompanying the storms. Although it is not yet possible to determine the extent of the participation in the corrosion by the acid of such an origin because of the unsolved difficulties of the experimental methods, nevertheless it must be assumed that this amount of acid constitutes a considerable denudative factor, especially in the tropics, where the atmospheric electric discharges are of consistent frequency.

Because of its importance among the possibilities of non-karstic corrosive processes on the limestone by the soil solutions, the action of phosphate solutions must definitely be stressed. For example, that of calcium dihydrogen phosphate, which reacts with limestone to form calcium monohydrogen phosphate:

$$CaCO_3 + Ca/H_2PO_4/_2 \longrightarrow 2\ CaHPO_4 + H_2O + CO_2 \qquad /13/$$

Ammonium phosphate, which occurs in the rendzina soils of limestone mainly as a product of the decomposition of animal bodies, acts on the limestone as follows:

$$\underset{/solid/}{3\ CaCO_3} + \underset{/solution/}{2\ /NH_4/_3PO_4} \longrightarrow \underset{/solid/}{Ca_3/PO_4/_2} + \underset{/solution/}{3\ /NH_4/_2CO_3} \qquad /14/$$

If the volume of the solid tricalcium phosphat formed /calculated from the molecular volume/ is taken as 100, then the unit volume of the mass of the starting $CaCO_3$ solid is 110.7. That is, the double decomposition reaction is accompanied by a volume decrease, and so it can occur even deep in the structure of the limestone. If the new solid mass formed, which replaces the original solid mass in the stone, does not occupy the same volume as the starting mineral, then unfilled spaces remain around the new formation in the structure of the stone /its pore volume increases/. Thus, the aggressive solution can penetrate deep into the interior of the layers, where the total transformation of the original material can be brought about in a very large thickness.

This refers too to all such double decompositions which result in solid reaction products and in which the product formed has a higher mineral density than that of the initial solid phase. This is also the case for the reactions of iron salts with limestone, e.g.:

$$CaCO_3 + FeSO_4 = CaSO_4 + FeCO_3 \qquad /15/$$

Naturally, not only the sulphates, but also the salts of iron formed with other strong acid radicals can easily bring about the double decomposition, all the more so because the molecular volume of iron carbonate /siderite/ is smaller /30.6/ than that of calcium carbonate /36.9/, and the exchange takes place in a 1:1 molecular ratio.

In the above example, a classic case was introduced of the epigenization of limestone by iron salts.

It is worth mentioning that the solid siderite crust forming on the boundary surface between the limestone and the soil can not impede the effect of the iron sulphate in the direction of deeper limestone levels, because it is soon dissolved by the carbonic acid-containing soil solutions. In the presence of water and oxygen /the karstic rendzina soil reaction medium corresponding to this/, the ferrous carbonate is sooner or later oxidized to ferric oxide. This can accumulate in the soil as either the dark--red haematite /Fe_2O_3/, or the brown limonite /$2Fe_2O_3.3H_2O$/:

$$2\ Fe\ CO_3 + 1/2\ O_2 \longrightarrow Fe_2O_3 + 2\ CO_2 \qquad /16/$$

$$4\ FeCO_3 + O_2 + 3\ H_2O \longrightarrow /Fe_2O_3/_2 \cdot /H_2O/_3 + 4\ CO_2 \qquad /17/$$

It is probable that, similarly to the process of siderite formation, many other exchanges occur for the limestone. Thus, the formation of glauconite and flintstone, and the substitution of sulphides of the heavy metals /e.g. pyrite/ in place of the calcite crystals /pseudomorphs/, may be the results of equivalent processes. ELIE DE BEAUMONT /referred to in CAYEAUX /1935// is surely right when be assumes that the explanation of the subsequent dolomitization of limestone in contact with sea-water is also to be sought in this phenomenon. In this case the magnesium chloride of the sea-water reacts with the calcium carbonate and the well-known double salt dolomite is obtained. The reaction is possible even in the interior of the limestone, because the density of the double carbonate, which is more poorly soluble than the calcium and magnesium carbonates, is much higher than that of calcite.

$$\underset{/solution/}{MgCl_2} + \underset{/solid/}{2\ CaCO_3} \longrightarrow \underset{/solid/}{CaCO_3.MgCO_3} + \underset{/solution/}{CaCl_2} \qquad /18/$$

$$2\ V_1 = 73.8 > V_2 = 63.6$$

A role is also played in the non-karstic corrosion of limestone by the often appreciable amounts of ammonium sulphate in the soil:

$$CaCO_3 + /NH_4/_2\ SO_4 \rightleftarrows CaSO_4 + /NH_4/_2CO_3 \qquad /19/$$

It should be taken into account, however, that this reaction takes place in the directionof the upper arrow only when the compounds on the right side of the equation are more dilute than those on the left side. That is, the continuity of transportation away of the calcium sulphate and ammonium carbonate formed must be provided by some effect such as the motion of the soil water, or a biogenic force. If, however, for some reason the concentrations are higher on the right side /e. g. in sea-water/, the double decomposition proceeds in accordance with the lower arrow /BECK 1968/.

The corrosive action of aluminium sulphate, if present in the soil, proceeds in an intersting way:

$$\begin{aligned} &6\ CaCO_3 + Al_2/SO_4/_3 + 6\ H_2O \\ &= 3\ CaSO_4 + 3\ Ca/HCO_3/_2 + 2\ Al/OH/_3 \end{aligned} \qquad /20/$$

It should be noted that the above reaction takes place only in neutral or acidic soils. In aqueous medium the acidically hydrolyzing aluminium sulphate is first consumed in decreasing the alkalinity of the soil, according to the following equation:

$$Al_2/SO_4/_3 + 3\ Na_2CO_3 + 3\ H_2O = 3\ Na_2SO_4 + 2\ Al/OH/_3 + CO_2 \qquad /21/$$

In order for us to form as complete a picture as possible of the effective forms of non-karstic corrosion, which has received fairly scant attention in the karst literature, it must still be mentioned that the dynamism of the dissolution may be significantly affected not only by the possible formation of chemical bonds with the various ions occurring in the soil solutions, but also by their simple mass actions, and in such a way that the effectiveness of the hydrocarbonate dissolution is <u>indirectly regulated</u> merely by their presence.

It is known that the solubility of a salt decreases in the presence of a salt of the same ion, whereas it is increased by the presence of a salt of different ions /GRÓH 1939, PAPP 1954, etc./. Thus, for example, the solubility of sodium chloride can be decreased by magnesium chloride, but at the same time the alkali chloride content /NaCl, KCl/ of the water increases the solubilities of calcium carbonate, calcium sulphate, calcium phosphate, etc. The solubility of $CaCO_3$ is similarly increased if the soil solution contains magnesium chloride, for example.

The modern view is that the hydrocarbonate dissolution of limestone is decreased by the other dissolved carbonates by changing the value of the denominator, K_t, of equation /6/ to a minimum. This has the result of increasing the accessory carbonic acid necessary to keep the calcium in solution. Because of this, natural karst waters, which always contain greater or lower amounts of carbonates of other ions too, generally require more free carbonic acid than that calculated on the basis of the calcium hardness.

According to PAPP /op. cit. p. 39/, the practical extent of this increased requirement is for the most part not appreciable, because especially in hard waters, which usually contain other carbonates too, compared to the otherwise considerable amounts of equilibrium carbonic acid the extra CO_2 requirement is insignificant. At the same time, it should also be taken into account that the decrease in the solubility of $CaCO_3$ produced by salts of the same ion may easily be counterbalanced by those salts of other ions which are always present in various amounts in karst waters, and which generally tend to increase the solubility of the $CaCO_3$. This means, therefore, that in the majority of cases the data of Table 4 calculated from equation /6/ do in fact correspond to the accuracy requirements of a good approximation.

In this short section we have by no means exhausted all the factorial possibilities of non-karstic corrosion of limestone in nature. We have attempted to stress only the most important of the components, as reflected in their observable, objective effects.

It must be pointed out, however, that the extremely fact--requiring and labour-consuming study of the many details and the evaluation of the extents of the effects involved in the question forms one of the perspective tasks of karst science. The future answers to these questions may provide very much to the entire karst science; it may well be that a certain fundamental reevaluation of the present axioms of karst theory will be necessary. But primarily perhaps we can still expect an impetus from the growth of the information available, in the settling of divergent problems of the denudation-dynamism of the climate zonal karst regions.

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L. J a k u c s

THE ROLE OF CLIMATE IN THE QUANTITATIVE AND QUALITATIVE CONTROL OF KARSTIC CORROSION

In the classic period of karst-morphological researches, highlighted by the names of ECKERT, GRUND, CVIJIC, KREBS, KATZER, MARTEL, PENCK etc. and by a deductive analysis of the karstic phenomena and processes of the temperate zone, a synoptic approach to karsts was developed, an approach that generalized on a global scale the forms and contents of the system of karst categories characteristic of Central and Southern Europe. In other words, the geomorphologists, of that time considered the characteristic features of the Dinaric Karst, of La Causses /France/, etc. to be the morphological criteria of karsts in general, For this reason, any limestone area in which these features could not be indentified was not even considered a karst in most of the cases.

This principle is reflected by almost all karst definitions of the first half of this century and the approach of various authors to the problem is also basically brand-marked by this attitude. The geomorphologists recognized no qualitative but quantitative differences to be manifested in by the various climatic zones with regard to karstification. Hence, those early descriptions of totally different type, which reported on limestone denudations /e.g. DANES 1914, 1916. H. LEHMANN 1936, MEYERHOFF 1938, etc./, could enjoy a rather limited scope of interest and did not awaken any attention even though their authors may have spoken of karstification in these cases, too. Inspired in their developments by DOKUCHAEV's teachings, Soviet geomorphologists /MAKSIMOVICH 1947, APRODOV 1948, GVOZDETZKY 1947, 1950/ were the first to emphasize that the notion of karstification should be widened on the basis of certain criteria of climatological zonring. Thus, besides normal karstification and associated classical karstic forms, they already distinguished the thermokarst /forst-induced karst/ of the glacial belt and of the tundra areas and did describe both the processes of pseudokarstic mechanism and the resultant specific landforms. /For additional information, see BOC 1957/.

These studies were soon followed by pioneering publications evaluating the variety of specific high altitude karstic forms /RATHJENS 1951, 1954/ and then, almost simultaneously with the Soviet developments, by H. LEHMANN's /1948/ and BÜDEL's /1951/ first works which, unlike their earlier publications, presented in the light of genetic classification the qualitatively quite peculiar morphological products of tropical karstification.

After that, in the 1950's and 1960's the number of studies on climatical karstic morphology by both Hungarian and foreign authors increased by leaps and bounds, and a considerable progress was made, above all, in the understanding of tropical karstic processes and phenomena. On one hand, papers of general character on phenomenological investigations were published, on the other hand, newer regional descriptions were produced.

Of the first group the works of H. LEHMANN /1954/1, 1956, 1960/, WISSMANN /1954/, KOSACK /1952/, CORBEL /1954, 1955, 1959, 1961/, SZABÓ /1957/, GVOZDETZKI /1958/, KLIMASZEVSKI /1958/, BIROT /1959/, RENAULT /1959/, BÜDEL /1963/ and SWEETING-GERSTENHAUER /1960/ are most important, whereas of the regional landscape descriptions, which might be regarded as being of classical weight, the publications of H. LEHMANN /1954/2, 1955/, CRAMER /1955/, GLENNIE /1956/, WISSMANN /1957/, GVOZDETZKI /1958/, KUKLA /1958/, SAINT-OURS /1959/, SUNARTADIRDJA-LEHMANN /1960/, GERSTENHAUER /1960, 1966/, WHITE /1962/, SMITH /1963/, DOUGLAS /1964/, MAXIMOWITSCH /1964/, VERSTAPPEN /1965/, TSCHIKISCHEV /1965/ and ROSE /1966/ have to be quoted. As for the Hungarian authors, a few comparatively more important literary products of this kind have even be on critically reviewed by A. KÉZ /1959, 1960, 1963/, and D. BALÁZS. Moreover, D. BALÁZS was in the lucky position that he could supplement the data known from literature sources with his local observations of his own.

However great number of works of general and regional object were published on the morphological effect of climatic changes on karstification, the lack of a uniform stand as to the differences in dynamism of karstification of different climatic zones is still obvious and the conception some authors have inherited from the classical karst-morphological school with regard to the interpretation of karstic corrosion mechanism is still confronted with irreconcilable contradictions when compared with the ever increasing multitude of observed facts.

In fact, according to the conventional model of the mechanism of karstic corrosion, as expounded in text-books, the CO_2-absorbing capacity of wated and, consequently, its corrosive power would be inversely proportional to temperature. Thus its dissolving power in polar and other cold regions /e.g. high mountains/ would be higher than that of waters of higher temperature characteristic of the tropical zones. In reality, however, the karstic forms virtually observed in tropical karst areas are suggestive of denudation phases incomparably more advanced as compared to those occuring under cold climates, in almost all of the cases.

With the impressive results of J. CORBEL, the prominent French investigator of karsts, who published in a series of papers such information on the chemical composition of the waters of rivers draining karst areas of different climate which, beside being virtually observed and controllable facts, would readily contribute to the sharpening of the above contradiction it became particularly difficult to unravel the puzzle. Nota bene, CORBEL pointed out /1954, 1955, 1959/ that the waters of rivers draining karstic surfaces of cold climate were carrying tenfold the amount of dissolved calcium carbonate transported by rivers originating in limestone areas of hot climate. From this observation, he drow the unambiguous conclusion that the rate of karstification in a cold zone is much more rapid than under a warm climate.

For a comparison of the rates of karstic denudation, he compared his regular, daily measurements in the rivers Kissimmee, Florida, USA, and Tanana, Alaska, USA, with data on river waters of other regions. His published results of these comparisons, which are selectively presented in Table I. have since become - we might say - classical.

Table I

Quantitative characteristics of the karstic denudation of limestone surfaces according to J. CORBEL

Characteristics and location of investigated area	Rate of denudation m^3/year/km^2 or mm%-/ year
Mountains with 2000 to 4000 mm of precipitation:	
a/ cold belt: /Northern Norvey, Britisch Columbia/	450
b/ warm belt:/Rio Usumacinta/	45
Low hills and plains with 1000 to 1600 mm of precipitation:	
a/ cold belt: /Quebec, Western Shotland/	160
b/ warm belt: /Rio Champotón Yucatan/	16
/KISSIMMEE, Florida/	5
Plains with 300 to 500 mm of precipitation:	
a/ cold belt: /TANANA, Alaska/ /Central Lapland/	40
b/ warm belt: /Chélif, Orleansville/	4
Plains with less than 200 mm of precipitation:	
a/ cold belt: /Lower reaches of the Mackenzie/ ...	14
b/ warm belt: /Rio Grande at Acacia/	1,4

With the knowledge of the chemical factors of limestone solubility in CO_2-containing water, however, it is aesy to realize that even though in case of the studied rivers of Florida and Alaska the figures calculated from observation data may apparently support CORBEL's suggestion, this approach to the problem has led to one of the most spectacular but false doctrines of geomorphology. This is a tragically typical example of how grave errors for science can ensue from a student's biased approach.

What should be noted in this connection is that in his basic assumptions CORBEL seems to have disregarded a few essential circumstances. Let us quote them herewith:

1. The carbonic acid content of water coming into contact with limestone is also controlled by factors other than the CO_2 contents and temperatures of meteoric waters and of the free air strata met with.

2. The role of the topmost soil layer of vegetation--clad karstic surfaces, layer containing decaying organic matter too, is much more important than that of the atmospherical CO_2 factor, as its soil "atmosphere" exposed to infiltrating water over a large area can have a CO_2 content several hundred times that of the free atmosphere /air/.

3. Also, marked differences /even in order of magnitude/ in the composition of soil atmosphere can be recognized when studied from the point of view of climatic zonality.

4. The CO_2 content of soil atmosphere may largely vary even within one and the same soil, a phenomenon for which the temperatures controlling the life rhythms of soil biotopes are primarily responsible.

5. According to investigations in France by TROMBE /1951/1-2, 1952/, the rendzinas, which in summer have a CO_2 content as high as 10 %, do not show in winter any carbon dioxide just like this component is virtually absent in the lean, vegetation-free soils of high-altitude mountains and polar to subpolar climatic zones.

6. In the humus-rich, rapidly maturing soils of high dynamism of the tropics the carbon dioxide regime is characterized by figures attaining the multiple of even the summer-time concentration levels of the soils of the temperate belt.

7. Limestone corrosion is not only due to the action of the carbonic acid of water; in fact, the other anorganic and organic acids and other compounds are also effective agents, their presence and activity being increased by heat and abundant moisture.

If J.CORBEL would have taken into consideration the above circumstances too, he would surely have formulated diametrically opposite statements as to the intensity of limestone corrosion in the different climatic zones, statements which would have been in accordance with both the up-to-date solubility theories and the inambiguous conclusions deduceable from the analyses of geographic forms. By the way, as would result from conclusions of this kind, tropical karstification must have a rate at least tenfold the figure of glacial karstification rather than just one tenth of it.

Would CORBEL ot mechanically and disregarding the other ecological circumstances - have considered the chemical compositions of river waters drained off from climatically different karsts, he must have realized that not even the data quoted by him did warrant that which the French student wished to prove with them. Namely, CORBEL totally disregarded the fact that even that fraction of precipitations is a limestone-dissolving agent which is finally re - absorbed from the soil by the plants and which then re - enters the atmosphere via evapotranspiration just like it is, say, that fraction which is lost to rived recharge on account of direct soil transpiration and evaporation. This water fraction is the more considerable, the warmer and humid the climate is, for the value of the coefficient of runoff for any area is defined, beside relief and lithology, first of all by the climatic factors of the region.

CORBEL, himself, indicates that wheras out of the 450 mm amount of annual precipitation of the area drained by Tanana river in Alaska, 450 mm /!/, i.e. 100 %, was found to run off a year, of the 1200 mm of annual rainfall of the warm drainage area of Kissimmee river in Florida as little as 175 mm /i.e. 14.58 % that is just one seventh of the annual rainfall in round figure/ could travel down the river.

As shown by the French writer, the 14.58 % runoff fraction of the rainfall carried away 5 m^3 of dissolved limestone a year from each km^2 area of the surface drained by the river. If, however, the total amount of the precipitations could flow down the channel of Kissimmee river too, this would mean that the amount of limestone waste would be as high as five times seven, i.e. 35 m³, per year per km², a figure not so much different from that given for the drainage area of Tanana river - 39.9 m³ per year per km². And yet, we have every right to make a calculation like this, unless we want to make ourselves believe CORBEL's naive argument /which the French writer did not formulate in strict terms, but which he still applied in his conception/ that the $CaCO_3$-dissolving power of rainwater would be defined by river-drianed percentage of rainfall.

Naturally, CORBEL's sophisticated theory has also other essential shortcomings. For instance, he does not take in to consideration that the carbonic acid reaction of $CaCO_3$ dissolution is expressed by a so-called reversible equation, in other words, that the equilibrium balance of the solution is very unstable being sensibly upset by any slight change in environmental conditions. Thus the water of a river affected by typical water--softening agents so eloquently illustrated by CORBEL himself/would not remain hard even if it were fed by hardest possible karstic waters in the source area of the river. For CORBEL writes, himself, that "in the environs of the Kissimmee the grassland is enmeshed by open water tables and by a promiscuous network of tributaries and ox-bows and that the temperature of river water is very high. Its mean daily temperature does rarely drop below 20 °C, being close to 30 °C for 3 months".

All the above circumstances must result in a rapid evaporation of the CO_2 content of the water and its intensive softening during the precipitation of lime. In other words, under circumstances like these, the composition of river water does not give any valuable information about the rate of karstification in the remote parts of the drained area. It does particularly not in the tropics where the degree of carbonic acid agressivity of the infiltrated waters primarily responsible for $CaCO_3$ dissolution and, consequently, for the actual corrosion too, are controlled by a soil atmosphere of high partial CO_2 pressure, and where the amount of dissolved CO_2 in surface rivers is very limited because of most unfavourable conditions for gas absorption. Let us recall in this connection the following chemical regularity: the dissolved gas content of the waters is defined by the partial pressure and temperature conditions existing in both the zone of infiltration and the stretches of runoff, and the higher the temperature of the space of reaction, the sooner a diffusion--absorption equilibrium between environment and solution will be established for one and the same interface.

Otherwise, it is quite natural that the composition of brooks and other watercourses, originating in karsted, barren surfaces of polar regions or high mountains, shows hardly any difference from that of waters in fissures of limestone masses or getting exposed in springs. Nota bene, in these cases there is not practically any noteworthy difference in temperature or partial CO_2 pressure between the air spaces coming into contact with the zone of infiltration on one hand, and with the zone of linear drainage /stretch of runoff/ on the other.

However, the grater the role of soil atmosphere and of ists, mainly biogenic, CO_2 concentration in defining the chemical character of infiltrated meteoric waters, i.e. the warmer the climate, the sharper the difference between the percentage of dissolution and that of removal by running water, to the point that the amount of river-transported calcium carbonate will be practically insignificant as compared to actual wearing away due to karstic denudation--circumstances mostly characteristic of present-day tropics.

Our above dispute with CORBEL has now led us to the formulation of one of the most important axioms of climato-genetic karst morphology. Accordingly, glacial karsts will develop into leached skeletal karsts, whereas the karsts of the tropical belt will be converted into massive karsts because the calcium carbonate masses dissolved in higher levels will reaccumulate in situ or in deeper levels, where $CaCO_3$ is transported vertically, only for the most part or where lateral transport, if any is confined to isolated, local spaces.

This is the explanation for the absence of tufa accumulations in polar karst areas and this is why polar caves are poor in dripstones /TELL 1962, ROHDENBUR-MEYER 1963/. On the other hand, this relationship also accounts for the extremely high rates of tufa accumulation both on the surface and underground, and of stalactitization in tropical karst areas.

It stands to reason that the karstic phenomena of the temperate zones are intermediate, in both quantitative and qualitative differences, between their tropical and glacial counterparts both on account of their geographic situation and climatico-genetical conditions.

However, it is only with a precise knowledge of the complexity and controlling factors of the processes of corrosion that all the above may become logically understandable. Therefore it is quite natural that CORBEL, who had disregarded almost all virtual facts and agents, must have arrived at erroneous results.

That the present writer still has had to enter into details with his criticism of CORBEL' theory /which may have deserved a better lot/ is basically due to the fact that his teachings have embarassed a number of outstanding, modern students of karstic phenomena. Nevertheless, CORBEL's investigations of climatic karst morphology have produced quite positive results as well. We mean here that the Fench worker has deeply astonished a number of research workers. These went then into defence and set to develop their "anti-CORBEL" which, of course, required to have hosts of new observed data.

The present writer is perhaps not wrong, if he supposes that a part of the valuable contributions to climatical karst morphology which appeared in the late 1950's and the 1960's and which have already been reviewed, were produced as a result of efforts made from these considerations. In Hungarian literature it is the paper of BALÁZS 1963 that provides a cross-section of the matter, though it appears that, as regards a virtually universal answer to the question, there is still a gap to be filled even in the internacional literature which is seemingly due to difficulties of data-collectin - a rather labourintensive and expensive work. Nota bene, CORBEL himself has collectend his 3000 /!/ data of measuring of Tanana and Kissimmee rivers since 1930, so even in view of the mass of information available deos it look appropriate to give an answer in which one is not obliged to relie merely on the "naked sword" of one's conviction of being right.

Even if the international scientific information of the last twenty years of climatico-morphological investigations of karsts were possibly insufficient for a spectacular disproval of CORBEL's teachings, it must be abundant enough to enable one to determine the relative rate of karstic corrosion and, more precisely, the percentage ratios of the agents involved, for each particular zone of the different characteristic climatognetic facies of karst morphology.

The present writer should like to point out once more that he considers, himself, this experiment to be a first approximation which still needs closer scrutiny in many a detail. Further precision is expected to be provided by calculations and assessments by other authors as well as by potencial clarification of new aspects as a result of new information still unknown to the present writer. Still we hope that our calculations and conclusions may, in their basic trends, be devoid of such grave errors as the publication of these results as a basic of discussion ought to be feared.

Let us depart, first of all, of the fact that on the basis of the differences in the karstic dynamims of limestone corrosion the present writer would be able to discriminate five such distinct climatic zones which are though not correlable in some respects with the classical zones of climatical geomorphology /DOKUCAEV 1883, PENCK 1913, BÜDEL 1948, 1963, BULLA 1954/1-2, H. LEHMANN 1954/1, 1956, LOUIS 1964 etc./, but which can be readily distinguished from one another both quantitatively /rate of karstification/ and qualitatively /variety of karstic forms/, these differences being obviously of climatico-genetic nature. The following zones of this kind can be distinguished:

1. High-altitude and periglacial zone comprising the karsts of polar and subpolar regions, the tjäle and tundra belt as well as subnival reaches of high-altitude mountains.

2. Temperate fluvial zone inclusive of the zone of grasslands.

3. Mediterranean zone together with desert steppe areas.

4. Zone of deserts.

5. Tropical karst-morphological province considered here to include the savannah belt and the zone of subtropical monsoon rains, too.

It is a matter of course, that any of the above five groups could be further subdivided. With the present-day availability of information, it would not yet be justified to do so on account of the possibility of secessive assessment of the degree of karstic dynamics.

If the present writer wished to express in percentage values the relative rates of karstic corrosion for different climatical karst-morphological zones, so the results of his calculations, checked multilaterally, would lead him to the conclusion that the ratio of the karstic dynamics of the zone of deserts corresponds, approximate by to 1 %, that of the periglacial and hihg-altitude regions to 6 %, that of the temperate zone 9 %, that of the Mediterranean to 12 %, while that of the tropical province to 72 %. In other words, the rate of tropical karstification is about 72 times that of karstification in deserts, sixfold the figure of the Mediterranean, eightfold that of the temperate zone and about twelve times that of high mountains. On the other hand, the Mediterranean karstic processes them selves attain about one and a half times the intensity characteristic of the temperate zone and twice that of the subnival and subpolar regions.

Even within these divergencies of the relative orders of magnitude of the rates of denudation, considerable differences are manifested with regard to the percentage shares of the various agents involved in corrosion, as illustrated numerically by Table II.

Table II

Percentage distribution of the genetic factors of corrosion in the most typical zones of climatical karst morphology

/original/. For explanation of numbers 1 to, 5 see Fig. 1.

	high-altitude + periglacial	temperate fluvial	medi- terranean	desert	tropical
1 =	45 %	7%	4 %	30 %	0,5 %
2 =	5 %	9 %	8 %	15 %	2,5 %
3 =	30 %	54 %	55 %	0 %	50,0 %
4 =	5 %	5 %	8 %	55 %	4,0 %
5 =	15 %	25 %	25 %	0 %	43,0 %

In Fig. 1. both the relative rates of karstic corrosion in the different climatical karst-morphological zones and the percentage distribution of the values of agents characteristic of the individual zones, have been shown combined. The figure readily demonstrates those substantial features which make it desirable to pay particular attention in these considerations to the qualitative specifics of the mechanism of dissolution which are at least as important and crucial as are the qualitative divergences of the dissolution processes of the individual climatic zones /Fig. 1./.

At closer scrutiny, however, Fig. 1. may also convince the reader that the single diagrams constituing the columns A-B-C-D-E can be compared with one another within one and the same column only and that comparisons both diagrams of adjacent or farther columns must be confined to relative terms comparisons in absolute figures being impossible. For, in exact quantitative terms, a 50 % share of the biogenic CO_2 factor in the tropical karsts accounting for 72 % of total dynamics /i.e. characterized by extremely high rate of karstification/ dinamics means substantially higher level of partial CO_2 than the same /50 %/ figure does for the temperate belt where the total intensity of corrosion is as low as 9 %.

Therefore, to make the absolute values of the factorial agents of karstic corrosion commensurable, the present writer has calculated these quantitative values by examining how great is e.g. the actual quantitative share corresponding to the 45 % ratio of atmospherical CO_2 in the periglacial zone. After that, the same was, successively calculated for an other percentage value and so on.

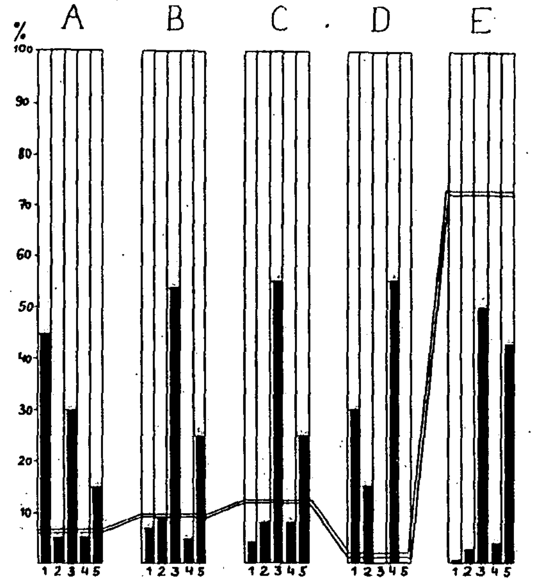

Fig. 1. Relative rates of karstic corrosion and percentage distribution of its agents in the most typical heteoclimatic zones of karst-morphological facies /original/.

Eyplanations: relative percentage intensity level of the dynamism of corrosive karstic denudation in the different climatic zones

Column A = high-altitude and periglacial /6 %/,
Column B = temperate-fluvial /9 %/,
Column C = Mediterranean /12 %/,
Column D = desert /1 %/,
Column E = tropical karst-morphological province /72 %/

Agents of karstic corrosion:
1 = CO_2 fraction of atmospherical origin,
2 = CO_2 deriving from inorganić soil processes /e. g. weathering/,
3 = biogenic CO_2 in the soil,
4 = share of other inorganic acids,
5 = share of organic acids /humic, acid, root fluids, etc./

The method of these new calculations consisted in determining the 45 etc. % values corresponding to 6 % characteristic of the periglacial zone and, naturally, the same method was used for the calculation of the values characteristic of the other climatic zones, too.

The resultant quantitative indices, which now can be really - and very instructively - compared both with one another and with other members of the same horizontal line, are shown in Table III. /In the last column of this table the sums of the quantitative values of the individual factors in the differenct climatic zones are given. Hence, this column is an expression of the global share in corrosion of the factor being considered./

Table III

Absolute values of the factorial agents of karstic corrosion in the most specific heteroclimatic zones as expressed by the ratios of the solubility levels characteristic of these zones /original/.
For explanations of numbers 1 to 5, see Fig. 1.

	high-altitude + periglacial	temperate fluvial	mediterranean	desert	tropical	global share of the factor in karst corrosion %
1=	2,70	0,63	0,48	0,30	0,36	4,47
2=	0,30	0,81	0,96	0,15	1,80	4,02
3=	1,80	4,86	6,60	0,00	36,00	49,26
4=	0,30	0,45	0,96	0,55	2,88	5,14
5=	0,90	2,25	3,00	0,00	30,96	37,11
Total	6,00	9,00	12,00	1,00	72,00	100,00

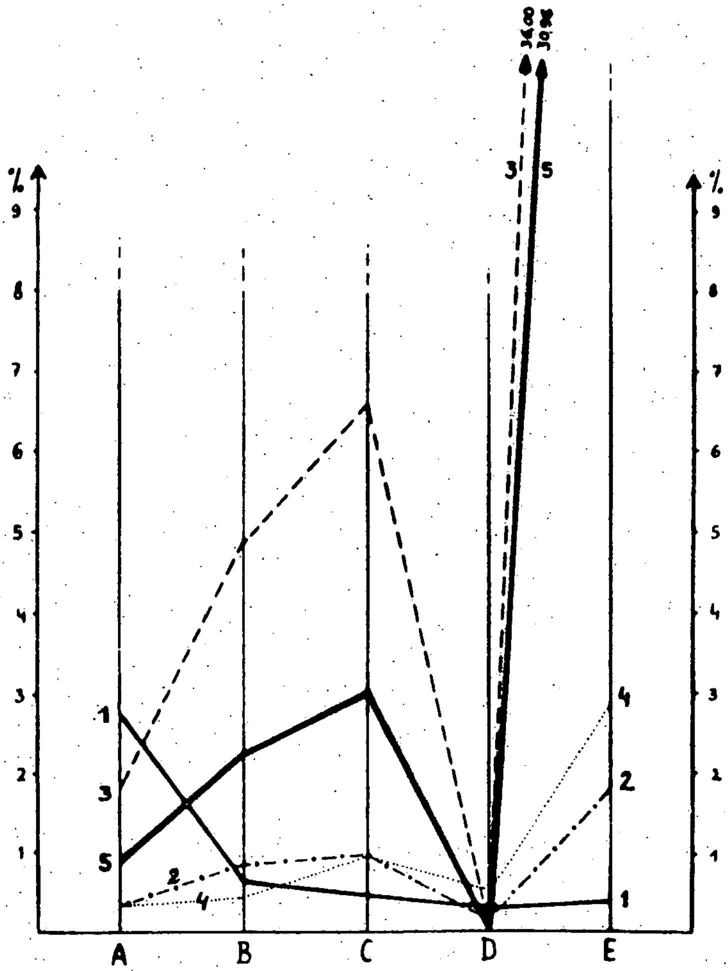

Fig. 2. Absolute values of the efficiency of the individual agents of karstic corrosion as found in the different climatic zones. For explanation of numerals and letter symbols, see Fig. 1. /Original./

If on the basis of Table II a complex diagram of the causal solubility factors of the different climatical facies is plotted, the undistorted, virtual order of magnitude of the manifestations of these agents will be brought into relief a result directly utilisable for the appreciation of karst-morphological problems /Fig. 2./.

In Fig. 2. the individual curves themselves are very instructive, but a comparison of the various diagrams may also prouve rather impressive. Let us review now in a little fuller detail the objective trends reflected by this extremely important figure.

First of all, the secessiveness of the behaviour of atmospherical CO_2 /Curve 1/, as compared to the curves representing the other corrosion factors, is obvious. Nota bene, whereas the lines of the other factors tend to rise markedly with the combined increase of temperature and rainfall, the line of atmospherical CO_2 shows, on the contrary, a trend of abating.

This abating trend is otherwise quite natural, for it reflects the validity for this case of HENRY-DALTON's gas absorption law, i.e. the fact that the amount of gas absorbed in cold water is higher than it is in warm one. /It is this law, and unfortunately just this one, that CORBEL referred to in formulating his ominous generalizations./

The HENRY-DALTON law in se does, however, not account for the differences in orders of magnitude between the "stages" of the descendent line, for the difference in degrees centigrade between the thermal levels of climatic zones A and B is not so high as to account for a considerable drop of this kind. This holds particularly true when considering the farther stretches of the curve, where some substantial thermal level differences /e.g. between B and E/ are though manifested but where these zones do still not differ so greatly from one another inasmuch as the corrosive action ot atmospherical CO_2 is concerned.

As for the cause ot the phenomenon, a possible explanation is certainly that, in A, much of water is precipitated /in form of snow or drizzle in other words, under conditions favourable for the absorption of gases/ and that, once precipitated on the surface, the snow will remain in contact with the air for a long time. It is quite probable that this is practically the only climatic stable dissolution-precipitation zone where an equilibrium of calcium carbonate is established in the infiltration zone mainly in depedence on the partial pressure of atmospherical CO_2 Accordingly, the total amount of absorbed atmospherical CO_2 here is defined by both simple physical gas absorption and the need for gases of the chemical reaction of hydrocarbonate dissolution.

Even though not striking, but still quite easily recognizable is another interesting feature of Curve 1. This consists in that the total amount of water-dissolved CO_2 of atmospherical origin in E /in the tropics/ is a little higher than it is in D. Since in E this cannot be due to a decrease in temperature one cannot help thinking in interpreting the phenomenon, that one has to do with a kind of reflection of the higher general CO_2 level of tropical atmosphere.

All in all, and in comparison to the other solubility factors, however, atmospherical CO_2 must be declared to be a factor rather little involved in karstic corrosion in all but the high-altitude and periglacial /subpolar/ climatic zones and that it is particularly in the tropical belt that its presence and action can be totally neglected in the background of other corrosion agents several times more efficient. /For instance, the effeciency of biogenic CO_2 is exactly 100 times that of atmospherical CO_2!/

Out of the additional diagrams of Fig. 2, the lines of No 2 and No 4 CO_2 produced by inorganic soil processes and other inorganic compounds /mainly acids/ testify to the fact that these factors show but a very low, and relatively subequal, rate of increase with the combined growth of poth temperature and humidity. This is a matter of course, since any higher temperature usually enhances inorganic weathering reactions and since moisture, the carrier of ionic reactions in the soil, renders all this possible. This is why the efficiency of these two factors in tropical limestone dissolution is, as a rule, twice to tenfold the figure characteristic of the other climatic zones, being under all climates except the polar belt, usually a little higher than that of atmospherical CO_2. And yet they have shared comparatively little in the dynamics of corrosion.

It seems to be proper to point out here already, than in climatic zone D /desert/ almost all corrosion factors are characterized by a very reduced rate of action. This is due solely to the lack of water so that the action of biogenic agents is radically cancelled and even the other chemical processes are heavily handicapped.

So it is essentially the poor CO_2, deriving from the air for the most part and transmitted mainly by dewfall, and the low-rate mineralogical reactions of "desert weathering" that are manifested, but their products, if any, are difficult to assess.

The behaviour of Curves 3 and 5 may look rather surprising. As pointed out above, these diagrams are expressions of the shares of the biogenic CO_2 and the organic acids of the soil as involved in karstic corrosion. As evidenced convincingly by the curves, both the factors are excessively sensitive to climate, being the essential agents of karstic corrosion over the major part of Earth's surface. Even in the mostly barren karst areas of cold climate category A, their role is of great importance, being readily manifested with the appearance of lichen over the smallest rock surfaces or with the poorest possible soil bacterial action. In temperate and Mediterranean karstic processes, however, they become crucial corrosive agents. The higher the compactness of the biosphere of earth's surface /particularly so, of its vegetation/ and the less its seasonal biological cyclicity, if any, the more progressive the growth of their efficiency. So in the tropics it is merely factors 3 and 5 that are responsible for the modelling of any karstic landscape.

By the way, the wealth of information published in international literature on geomorphology shows unambiguously, that in the tropics these two last-discussed corrosive agents /biogenic CO_2 organic soil acids/

may gain overhand with respect to the rest of the morphogenetic agents /e.g. linear erosion, sheetwash, derasion, etc./ not only in limestone-built areas, but in areas made up of other rocks as well. Thus in zones of this kind even polymineralic sectors /e.g. areas made up of granites, andesites, etc./ may often happen to exhibit macro- and microforms /e.g. bellshaped mounts, pinnacles, karrs, etc./ suggesting corrosive denudational processes.

An examination of Curves 3 and 5 in Fig. 2 may shed light upon another interesting realtionship. Nota bene, if the A-C stretches of the curves are compared with one another, it appears that the increase of biogenic CO_2 towards C is more progressive than in is the case with organic soil acids. In E, however, this initial realtive tendency of the two factors is rather eliminated, as compared to their absolute height levels 36.00 and 30.96, respectively. In other words, whereas in the Mediterranean zone for instance the corrosive efficiency of biogenic carbonic acid attains more than twice the figure of organic acids, under tropical climate this ratio tends to become an equation as one proceeds towards higher altitudes.

While exploring the causes of the phenomenon, one may have the impression as if the accumulation of biogenic CO_2 in the soil had a maximum level which the corrosive action of organic acids can even keep pace with under favourable conditions but which does not keep on increasing obviously because, one one hand, it is jeopardized by soil transpiration itself, on the other hand, because too high a concentration of CO_2 is a drawback

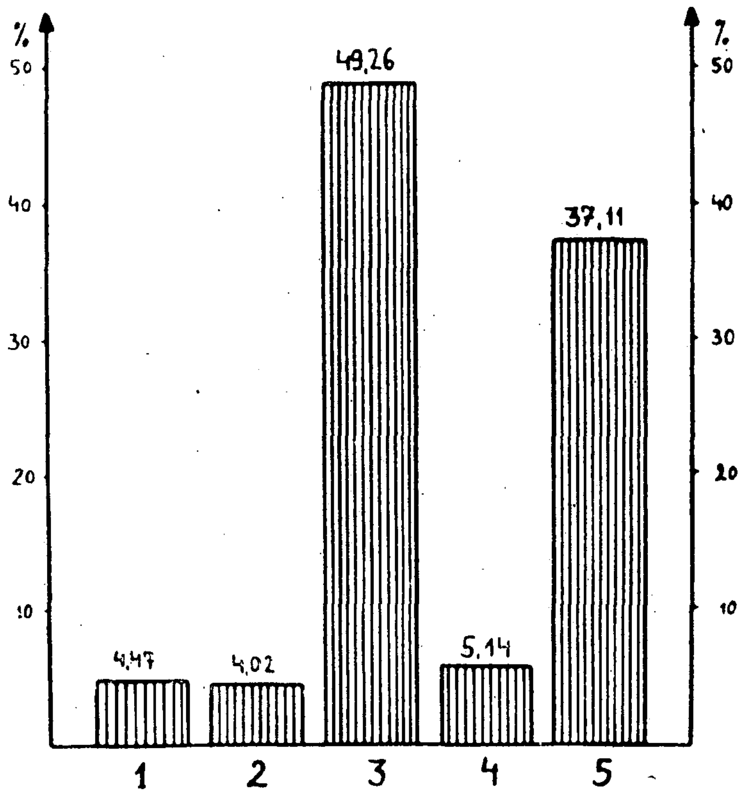

Fig. 3. Distribution of the main corrosive agents are reflected by the karstic denudation of calcereous rocks on the global /planetary/ scale /original/. For explanation of column numbers 1 to 5, see Fig. 1.

to the living conditions of the soil biotope itself /for it may stop the gas-producing biogenic processes themselves/. It if still very difficult, however, to formulate this theory in strict terms, for no direct investigations into this problem have sor far been undertaken under tropical climates. Thus it is quite possible that expedient investigations of coming years may bring into relief another aspect of the relationship.

To make clear the absolute global /planetary/ values of the limeston-eroding efficiency of the main agents of karstic corrosion, the present writer has also plotted in Fig. 3 the numerical data of the outside right vertical column of Table III.

In the light of the evidence provided by figure, we need not worry about formulating the most important result of the present writer's investigations. Accordingly, the natural karstic corrosion of calcareous rocks is geneticaly nothing else than the phenomena of the biological and chemical evolution of the rock-covering topsoil as reflected by the soluble bedrock.

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L. Jakucs

DYNAMISCHE UNTERSCHIEDE DES VERKARSTUNGSPROZESSES IN DEN MIKRORÄUMEN

Es ist bekannt, dass das Klima bei der Intersitätsregelung des Verkarstungsprozesses von entscheidender Bedeutung ist. Im Laufe unserer früheren Untersuchungen hat sich eine breite Skala von Beweisen erschlossen, die begründeten, die Klimavarianzen der Verkarstung in den Mittelpunkt der morphogenetischen Analyse zu stellen.

Wir können wohl sagen, dass die Karstkorrosion der Kalkgesteine im wesentlichen nichts anderes ist, als die formale Widerspiegelung der biologischen und chemischen Entwicklungserscheinungen der das Gestein überlagernden Bodensphäre im löslichen anstehenden Gestein. Es ist aber zunächst ein wichtiger Umstand, dass diese biologischen und chemischen Entwicklungserscheinungen in ihrer Grössenordnung und Beschafenheit entscheidend klimagenetisch orientiert sind.

Bei der Karstdenudation der gleichen lithologischen, tektonischen, orographischen, zunächst aber unterschiedlich klimazonenbedingten Kalksteingebieten ergibt sich also vielfache Unterschiede der Grössenordnung und der grundlegenden Beschaffenheit allein aus der Ursache, dass die Temperatur- und Niederschlagskennwerte dieser Räume unterschiedlich sind und deshalb an ihrer Oberfläche spezifische Vegetations-typen leben und sich verschiedene bodenbiologische /folglich auch chemische/ Vorgänge abspielen.

Die vorstehende Aussage wird durch die internationalen und ungarischen Forschungsergebnisse der letzen Jahre überzeugend bewiesen. Es ist also aktuell, einen Schritt weiter zu gehen. Wenn es sich nämlich beim Vergleich der voneinander geographisch entfernt gelegenen Gebiete als wahr erwies, dass die Differenzen der Niederschlagsmengen und der Wärmemengen - besonders durch biochemische Vermittlung - karstdynamische Stufungen hervorrufen, soll es auch dann wahr sein, wenn klimatisch unterschiedlich bedingte Gebiete miteinander verglichen werden, die voneinander im geographisch nicht weiten Abstand entfernt gelegen sind. Das heisst, die Entfernung spielt bei dieser Frage gar keine Rolle.

Anders gesagt soll das bedeuten, dass der Verkarsttungsprozess in einem bestimmten Mikroraum jeweils durch die mikroklimatologischen Kennwerte der betreffenden Stelle bedingt wird, die selbst nicht allein vom Mikroklima des Gebietes abhängig sind.

Die planetarische Zonalität des Mikroklimas kommt im Verkarstungsprozess soweit zur Geltung, wie sie innerhalb des Klimabereiches auf die Eigenarten und Verteilungsproportionen der einzelnen Mikroklimaräume bestimmend wirkt. Und soweit die unterschiedlichen lokalen Gegebenheiten hinsichtlich der Orographie, Exposition, des Windschutzes usw. innerhalb desselben Klimabereiches solche Kleinräume mit extremen Eigenschaften des Mikroklimas gestalten, deren Faktorkennzeichen von den allgemeinen Faktorkennzeichen der Klimazone erheblich abweichen, wird auch die lokale

Intensität ihrer Verkarstungsprozesse von dem für den Mikroraum /Bereich/ bezeichnenden globalen Verkarstungsprozess abweichen. Das intrazonale Auftreten der meisten karstmorphologischen Gepräge der Extrazonalität hängt damit zusammen. In einer Region muss also die Beschaffenheit des Abtragungsprozesses der Oberfläche so erläutert werden, als das statistische Mittel der einander nicht notwendigerweise ähnelnden konkreten Denudationsvergänge zahlreicher, die Region gestaltender Mikroräume.

Es versteht sich von selbst, dass sich unsere vorsthende Feststellung nicht allein auf die karstige Denudation bezieht, aber der Zielsetzung unserer Arbeit entsprechend wollen vor nun die Frage, dieselben Beispiele beibehaltend, weiter analysieren. Im folgenden müssen wir als das Wichtigste die kleinsten physisch-geographischen Landschaftseinheiten bestimmen, bei denen die die Intersitätsstufen der Verkarstung auslösenden Unterschiede des Mikroklimas in der Form noch zum Ausdruck kommen können.

Es ist merkwürdig, dass bisher keine Ansätze zum synoptischen Studium dieser Themengruppe von der Seite der Geomorphologen weder in Ungarn, noch im Auslande erfolgten. Deshalb sind wir gezwungen, uns ausser unseren eigenen Untersuchungen vor allem auf die von einigen bahnbrechenden Klimatologen, Pedologen und Biologen Kollegen im Laufe von ganz anders gerichteten Analysen erschlossenen Ergebnisse zu stützen. So denken wir vor allem an die Forschungen von R. WAGNER, die über die genaue Klärung der Begriffe der Mikroklimas unterschiedlicher Grössenordnung hinaus ein beträchtliches und längere Zeitreihen umfassendes wertvolles Beobachtungsmaterial über das Karstgebiet zur möglichen Beurteilung der morphogenetischen vermutlichen Verbindungen gewähren /WAGNER 1954, 1955/1-2, 1956, 1960, 1964, FUTÓ 1962, BÁRÁNY 1967 usw./. Aber sehr vielsagend sind die Untersuchungen von Pedologen - an unser Thema anschliessend vor allem von D. FEHÉR /1954/ - über die Bodenatmung, ferner die phytozoenologischen Forschungen, die die Pflanzenassoziationstypen eines Karstgebietes von homögenem Gesteinsmaterial in mikroklimatischer Interpretation analysieren /BACSÓ-ZÓLYOMI 1943, P. JAKUCS 1954, 1955, 1956, 1961, 1962/.

Hauptsächlich nach den oben erwähnten Autoren wissen wir, dass es z. B. an den Karstoberflächen der Ungarischen Mittelgebirge beträchtliche mikroklimagenetische Unterschiede der Bodenintensität gibt, und zwar nicht nur in den Vorgängen der Rhizosphäre der die nördlich oder südlich exponierten Hänge begleitenden eigenartigen Waldgesellschaften, Buschwälder und Steppenwiesen /also z. B. auch innerhalb einer einzigen Doline/, sondern auch in davon viel geringeren Raummosaiken /z. B. in der Wurzelkrone von zwei benachbart lebenden Pflanzenarten/. Besonders nachdrücklich bezieht sich das auf das gegenseitige Verhältnis der Kohlendioxiderzeugung, die von der Tätigkeit der Bodenmikroorganismen quantitativ in sehr empfindlicher Weise abhängig ist, und der Bodenatmung. Gerade diese sind aber hinsichtlich der Verkarstungsbereitschaft des vom Boden zum Karst hin versickernden Wassers die wichtigsten, agressivitätsbestimmenden Faktoren.

Wenn es also nachweisbar ist, dass es z. B. dei den Wärmemengen, dem Verlauf der Erwärmungs- und Abkühlungskurven, den Niederschlagsmenge, Bodenfeuchtigkeit usw. der N- und S-, sowie der O- und W-exponierten Hänge Unterschiede in mikroklimatischem Sinne, aber von bedeutender Grössenordnung gibt, ziehen diese als Postulate nach sich auch die Unterschiedlichkeiten der an ihnen lebenden natürlichen Vegetation und der damit im Zusammenhang stehenden Bakterienflora, Bodendurchfeuchtung usw. der Pedosphäre, woraus dann die partiale dynamische Teilung des Karstprozesses der Doline ergibt. Das heisst, die korrosive Denudation wird an den unterschiedlich exponierten Hängen der Doline zwangsmässig anderartig sein. Aus diesem Unstand ist doch bereits nicht schwer die Folge zu ziehen, dass die Form und das Gesischt der Karstdolinen die formale Widerspiegelung der Anordnung ihrer Mikroklimaräume sind.

Im weiteren untersuchen wir einige von den Voraussetzungen der Aussage, die im vorstehenden nur noch als Arbeitshypothese abgefasst wurde.

WAGNER ermittelt unter anderem in einer Doline des Középbérc auf dem Bükk-Plateau im Vergleich zu den früheren Quellen /BACSÓ-ZÓLYOMI 1934, LÁNG 1953, GEIGER 1961, FUTÓ 1962/ ausführlichere Angabenreihen von Mikroklimamessungen, mit deren Hilfe er auch in der Grössenordnung der Werte die eigenartigen Wärmeunterschiede des Innern der Dolinen und ihre Tendenzen genau konkretisiert /WAGNER 1960, 1963, 1964, AMBRUS 1965, GÖMÖRI 1967/. Danach erwärmen sich in Ungarn am kräftigsten und am meisten andauernd die südöstlich, südlich exponierten Hänge der Dolinen, während die nordöstlich, nördlich exponierten Flanken am kühlsten erhalten bleiben. Die O- und W-Expositionen einer Doline miteinander verglichen sind aber immer die gegen O hin liegenden Flanken die wärmeren.

Die Temperaturunterschiede der einander gegenüber liegenden Hänge sind besonders in den Morgenstunden auffallend, da es in den bodennahen Luftschichten der O- und SO-Expositionen im Sommer Wärmegraddifferenzen von sogar 10 oder noch darüben °C entsprechend vorkommen kann. Am Nachmittag hingegen, da die westlichen Hänge der direkten Sonnenstrahlung unterliegen, bleiben die Wärmegradunterschiede umgekehrt verglichen niedriger erhalten.

Noch merklicher zeigt sich die Unterschiedlichkeit der Erwärmung bei Tag und des Wärmebetrags der südlichen und nördlichen, und zunächst darüber hinaus der östlichen und westlichen Expositionen beim Vergleich der Bodentemperaturen. In Abbildung 1. werden die auf eine Bodentiefe von 2 cm bezogenen Beobachtungen der in vier unterschiedlichen Expositionen angelegten Bodenklimastationen einer Doline dargestellt.

Die Grössenordnungen der Amplitude widerspiegeln vornehmlich die Unterschiede der Hangneigungen; aber insbesondere der eigenartige Verlauf der Erwärmungskurven der östlichen und westlichen Expositionen, die Verschiebung der Maximumstellen, die steigenden Kennwerte des die Erwärmung bezeichnenden Flügels des Diagramms enthalten partial auch die Gepräge der übrigen Faktoren, die eine erhöhte Kontinentalität der Osthänge verursachen.

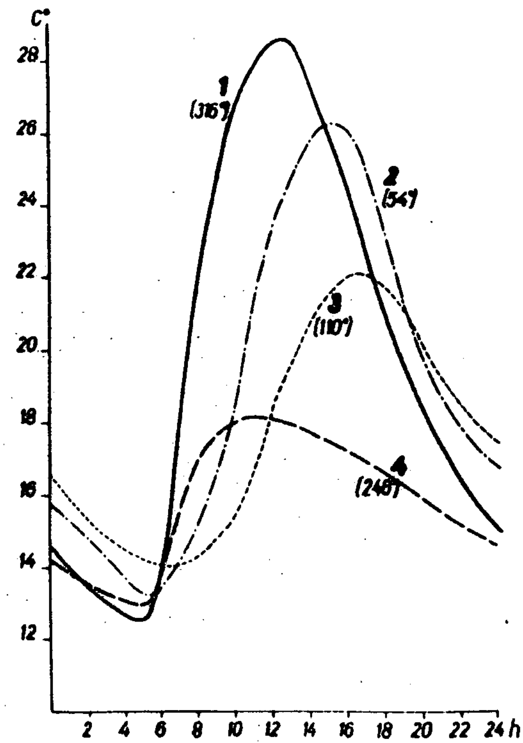

Abb. 1. Bodentemperaturkurven gemessen in einer Tiefe von 2 cm der bei unterschiedlichen Expositionen angelegten Bodentemperatur-Messstationen in einer Doline des Középbérc des Bükkgebirges. Die Diagramme des Wärmeverlaufs von 24 Studen sind an Hand der Durchschnittswerte des an vier aufeinander folgenden Tagen /6-7-8-9 August 1965/ aufgenommenen Beobachtungsmaterial von R. WAGNER verfertigt.

In dieser Beziehung ist die komplexe Durchsetzung von mehreren Faktoren wahrzunehmen. Von ihnen heben wir nur einige hervor:

1. In den Morgen- und Vormittagsstunden ist es im allgemeinen weniger bewölkt, als nachmittags.

2. Die Südexposition erhält bereits am Morgen den aus der direkten Sonnenstrahlung stammenden und für die Erwärmung des Bodens massgebenden Wärmebetrag. Während der gleichen Zeit wird der nördlich exponierte Boden durch die Luft von niedriger spezifischer Wärme infolge der Wärmeleitung nur sehr langsam erwärmt. In den Nachmittagsstunden hingegen, da die W-Expositionen die direkte Sonnenstrahlung erhalten, kann die Abkühlung durch Wärmeausstrahlung der O-exponierten Hänge nur langsam vor sich gehen, da sich die mit dem Boden in Kontakt stehende Luft bei Tag stark erwärmte. Die O-Exposition ist also die ganze Strahlungsdauer hindurch warm, während die W-Expositionen nur am Nachmittag warm sind.

3. Die Starkgegen sind im Sommer nachmittags häufiger, als vormittags. Deshalb wird die direkte Strahlungswärmekalorie in den Tageszeiten der intensiven Erwärmung der westlichen Expositionen für die Verdunstung öfters verbraucht, als am östlich exponierten Hang.

4. Wegen der gleichzeitig mit dem Regenfall vorherrschende und den Einfallswinkel des Niederschlags regulierende Windrichtung /W-NW/ erhalten die östlich, als die westlich und nordwestlich exponierten Dolinenhänge von gleicher Neigung.

Die Tagesgänge der eigenartigen Bodentemperatur der unterschiedlichen Expositionen wirken natürlich nicht nur in der Bodentiefe von 2 cm, sondern bestimmen praktisch den Wärmeheushalt des völlig aktiven Bodenprofils. Die Vorgänge der Pedosphären der östlich und südlich exponierten Dolinenhänge werden dadurch immer extremer im Vergleich zu denen der westlich und nördlich exponierten Hänge. Das ist besonders gut ersichtlich aus der täglichen Temperaturschwankung in der Bodentiefe von 30 cm, in welcher Tiefe bei den westlich exponierten Böden eine Temperaturveränderung kaum bemerkbar ist.

Die oben dargestellten sehr bedeutsamen Unterschiede - innerhalb der Doline - im Charakter der Wärmemenge, der Niederschlagsmenge und der Erwärmung wirken durch mehrseitige Verbindungen auf die CO_2-Produktion des Dolinenbodens, die Intensität der Bodenatmung, die Bodenfeuchtigkeit, die qualitative und quantitative Zusammensetzung der Vegetation und der Mikroflora, Fauna usw. des Bodens und durch all dies, letzten Endes, selbst auf den Verkarstungsprozess, auf dessen lokale dynamische Unterschiede.

Der Feuchtigkeitsgehalt des Bodens der unterschiedlich exponierten Dolinenhänge steht z. B. u. a. in unverkennbarer Beziehung zum Ausmasse der Sonneneinstrahlung und zum Erwärmungsgrad. Das wird auch durch die Ergebnisse unserer ausführlichen Dolinenaufnahme bestätigt, die wir in einer bepflügten und so zur Untersuchungszeit /Mai 1962/ als vegetationslos zu betrachtenden Doline des Nord-Borsoder Karstes /Etwa 1300 m weit in NNO Richtung vom Glockenturm der reformierten Kirche von Jósvafő entfernt/ unternommen hatten. Die Ergebnisse der Bestimmung durch Austrocknenverfahren des Feuchtigkeitsgehaltes der aus einem 10 cm tiefen Bodenhorizont entnommenen Proben haben wir in Abbildung 2 in interpolierter Form dargestellt.

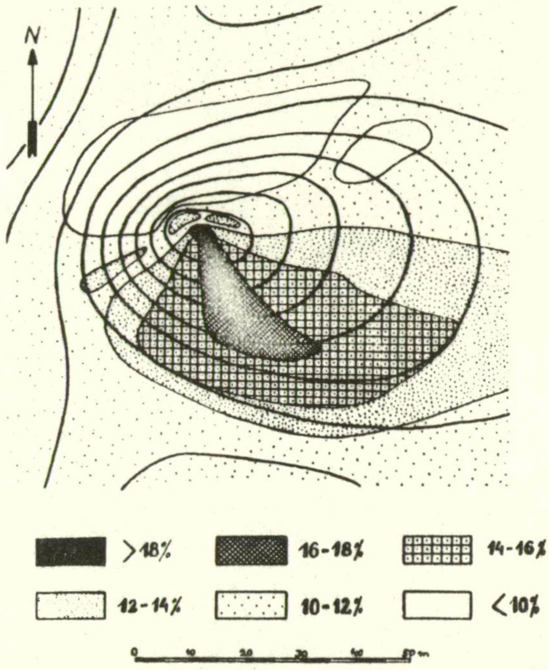

Abb. 2. Beispiel für die Anordnung der Bodenfeuchtigkeit in einer vegetationslosen /bepflügten/ Doline von gleichmässiger Bodenbeschaffenheit in einer Tiefenlage von 10 cm. Die Werte der Bodenfeuchtigkeit sind in Gewichtprozent ausgedrückt eingetragen. Die Höhenlinien stellen die Isohypsen von je 1 m Abstand dar. Die Interpolation der Karte haben wir an Hand von 81 Beobachtungen /nach einem Gitternetz von 10 m-Quadrat/ durchgeführt /originell/.

Im vorangehenden haben wir bestätigt, dass es auch innerhalb einer einzigen Doline beachtenswerte Unterschiede der Bodentemperatur und der Bodenfeuchtigkeit gibt und die Anordnung dieser Faktoren mit dem Verhältnis nach Himmelsrichtungen verbunden ist. Die weitere Ausführung der Gedankenreihe in der Richtung des Beweisschlusses über die mikroklimatische Bedingtheit der dynamischen Differenzen der Karstkorrosion liegt auf der Hand.

Einer der grundlegenden Sätzen der Biologie auf der Ebene der Handbücher ist, dass die Lebensfunktionen der im Boden lebenden Mikroorganismen auf die Wärmemengeveränderungen des Bodens empfindlich reagieren.
D. FEHÉR /1954/ teilt das von RUSSEL veröffentlichte Diagramm mit, das die auch vom Tagesgang der Temperatur empfindlich abhängigen Schwankungen der Bakterienanzahl des Bodens deutlich darstellt /Abb. 3/.

Im Besitze von seit langem durchgeführten Versuchsreihen und eines Beobachtunsmaterials weits aber FEHÉR auch auf den Umstand hin, dass die optimale Temperatur an sich noch kein ausreichendes Kriterium für das Antreiben einer Population der Bodenmikroorganismen sei, sondern es kann allein durch die gleichzeitige Einwirkung der Temperatur- und Bodenfeuchtigkeitsoptima gewährleistet werden. Nach seinen Untersuchungen, die neulich auch von BECK /1968/ unterstützt wurden, kann das Daseinsoptimum vom Gesichtspunkt der Virulenz und Vermehrung der Bakterienflora im Boden aus durch eine Temperatur von 25° C und gleichzeitig die etwa 25 Gewichtsprozent ausmachende Bodenfeuchtigkeit gesichert

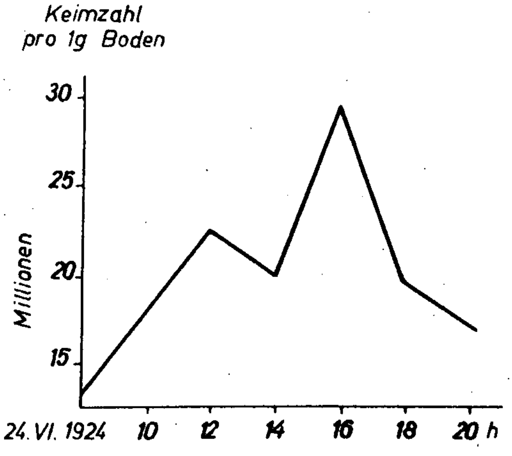

Abb. 3. Veränderung der Anzahl der im Boden lebenden Bakterien 12 Studen hindurch in Abhängigkeit des Tagesganges der Temperatur des untersuchten Bodenhorizonts /Beobachtung von RUSSEL 1924/.

werden, natürlich unter den entsprechenden Bodendurchlüftungsbedingungen. Die Abnahme oder Zunahme eines jeden Faktors ergibt sogleich die kräftige Abnahme der Bakterienanzahl. Die Grössenordnungen der Zusammenhänge können wohl in Abb. 4. auch zahlenmässig erfasst werden.

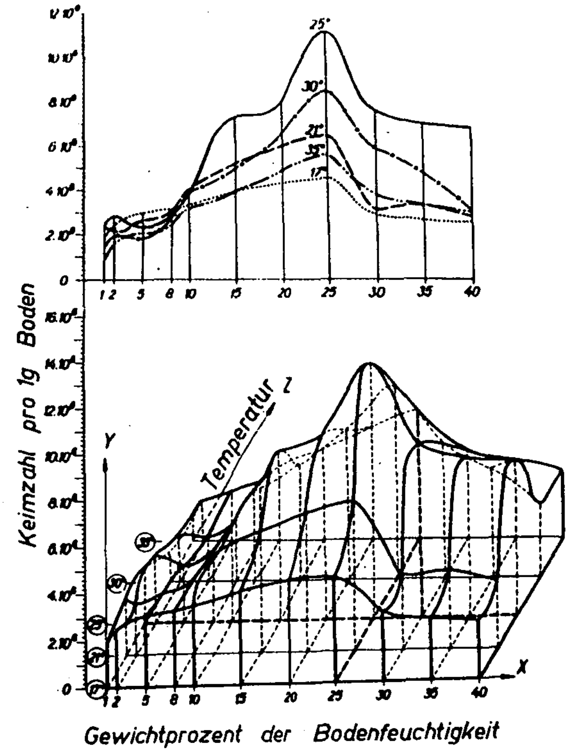

Abb. 4. Die biologische Aktivität des Bodens darlegende räumliche Kurve, woran die Widerspiegelung der komplexen Einwirkung der Temperatur und der Feuchtigkeit durch die Bodenbakterienanzahl auch zahlenmässig abzulesen ist. Die Werte der X-Achse bezeichnen die Bodenfeuchtigkeit in Gewichtsprozent, die der Z-Achse die Bodentemperatur in °C angegeben, während die Werte der Y-Achse die auf 1 g Boden bezogene Bakterienanzahl andeuten. Oben ist das Projekt der Kurven in der X-Y Ebene hervorgehoben /nach FEHÉR/.

Bei den Klimabedingungen in Ungarn sind die Wandlungen der Temperatur und des Wassergehaltes des Bodens im allgemeinen von gegensätzlicher Ausbildung. Im Sommer, da die Temperatur den optimalen Wert erreicht, ist der Wassergehalt des Bodens niedrig. Oder sollte er bei einem stärkeren Niederschlag vorübergehend höher sein, so wird die optimale Ausbildung der biologischen Aktivität durch die höhere Temperatur infolge des Wärmeentzuges durch Verdunstung wieder gehemmt.

Diese für unsere Klimazone bezeichnende Gegensätzlichkeit tritt wegen der Expositionen von hohem Werte in den Dolinen in noch erhöhtem Masse in Erscheinung. Deshalb wird es im Boden der rasch und stark erwärmenden, östlich und südlich exponierten Dolinenhänge derartige kürzere Perioden geben, wobei die nahe optimalen Temperatur- und Feuchtigkeitsbedingungen der biologischen Aktivität auftreten /kräftige Insolationen nach Sommerregen in der Nacht oder am frühen Morgen/. Zu solcher Zeit erreichen der plötzliche Anstieg der Bakterienanzahl und die Erhöhung der damit einhergehenden CO_2-Erzeugung im Boden sprunghafte Höchstwerte. Im allgemeinen aber werden die Einwirkungen der höheren Wärmebeträge durch die oft lang andauernde kräftige Austrocknung des Bodens im Sommer für die Lebensbedingungen der Mikroorganismen ungünstig beeinflusst, und deshalb wird an solchen Gehängen mit extremen Amplituden der Erwärmung und Bodenfeuchtigkeit über die weitgehenden Ausschwunge der biologischen Aktivität auch der Intensitätsverlauf der Karstkorrosion weitbegrenzte Schwankungen aufweisen.

Dagegen gibt es bei den Böden der nördlich und westlich exponierten Dolinenhängen - wie gesehen - weder in bezug auf ihre Temperaturveränderungen, noch auf ihnen

Feuchtigkeitsgehalt keine Extremitäten von ähnlichem Ausmass. Der im allgemeinen niedrigere, doch gleichmässigere Temperaturgang und der bedeutendere Bodenfeuchtigkeitsgehalt gewähren einen von Fall zu Fall unterschiedlichen Grad aufweisenden, doch unbedingt ausgeglicheneren Horizont für die Bodenmikroorganismen. In impliziter Form haben wir damit bereits auf die vielleicht entscheidendsten Ursachen der die Bodenwässer der untersuchten Expositionen bezeichnenden weniger schwankenden, aber geringerer Korrosionsfähigkeit hingewiesen.

Im Zusammenhang damit ist es zu bemerken, dass R. WAGNER hinsichtlich der aus den Expositionsunterschieden der Dolinenhänge stammenden morphogenetischen Wirkung einerseits die Faktoren der Gesteinsverwitterung durch erhöhte Insolation der rasch erwärmenden O-exponierten felsigen Hänge, andrerseits die physischen Verwitterungsfaktoren der durch Dilatationsbewegungen erfolgten intensiveren lithoklasenbildenden Möglichkeiten betont. Zum Beweis der als sehr reell erscheinenden Vorstellung sind aber an den aus Kalkstein bestehenden Dolinenhängen bisher keine konkreten Untersuchungen durchgeführt worden, deshalb soll seine Ansicht hinsichtlich der Grössenordnung in der morphologischen Durchsetzung des Faktors vorläufig noch als Arbeitshypothese betrachtet werden.

Natürlich sind die behandelten mikroklimatischen Expositionskennzeichen in einer Doline nicht nur die quantitativen und qualitativen Determinanten ersten Ranges des Phytoedaphons, sondern sie begünstigen ständig auch die Struktur der Makroflora. Es sind z. b. im Bükkgebirge /Hosszubérc, Kismező, Nagymező/ oder im

Karstgebiet von Nord-Borsod /Verőtető usw./ an den südexponierten /in der Regel felsigen/ Gehängen der waldlosen Dolinen an waldsteppigen Arten reiche Steppenwiesen /Festucetum sulcatae/, dagegen and den Ost- und Westhängen und im allgemeinen auch an den Rändern /falls der Boden/ nicht tiefgründig ist/ mesophile Bergwiesen /Festucetum ovinae/ zu finden, während an den N-Hängen entweder die vorigen oder Haselsträucher /wenn sie felsiger sind: Coryletum avellanae/, an den nördlichen flachen Schultern mit tiefgründigen Böden oder an den Dolinesohlen mit mächtigeren Böden Borstgrasrasen /Nardetum strictae/ vorkommen. Wenn der Hangfuss der Doline felsig oder trichterförmig ist, so kann dort die Vegetation mit Hochstauden /mit Arten von Eisenhut, Aconitum, Gladiolus usw./ entwickeln /P. JAKUCS 1961/1-2, 1963/. Diese Pflanzengesellschaften deuten in den Dolinen an inverse Zonalität an.

Einen solchen Vegetationsumkehr hat sonst auch GEIGER /1961/ in der Doline Gstettneralm, Niederösterreich, ausgewiesen, ferner I. HORVÁT /1953/ in den Dolinen des Karstgebirges von Jugoslawien.

Es ist offensichtlich, dass in anderen Vegetationszonen /Höhenregionen/ andersartige Assoziationen vorkommen und ganz anders ist die Lage auch in einer waldbedeckten Doline. Aber die Differenzierung je nach der Exposition ist auch dabei charakteristisch. Und all das ist durch die Vermittlung der Pedosphäre von Einfluss auf die Verkarstung unter dem Boden, denn der gegen den Boden erhobene Anspruch der verschiedenen Pflanzenarten, sowie ihre Wirkung, die sie auf die Entwicklung den chemischen, den Mikroorganismus betreffenden, den Feuchtigkeits-, Durchlüftungs- usw. Zustand des Bodens ausüben, sind unterschiedlich.

Diese Zusammenhänge wurden hinsichtlich der Assoziationstypen der an den Karsten lebenden natürlichen Vegetation aus verständlichen Gründen in ihrer Grössenordnung noch nicht untersucht, hinsichtlich der Kulturpflanzen und vor allem einiger gewissen Holzarten verfügen wir doch seit langem über die entsprechenden konkreten Ergebnisserien.

In der Tabelle Nr. I stellen wir nach STOKLASA-DOERELL /1926/ für sechs Kulturpflanzen, ferner für vier Bodenbakterien ihre Kohlendioxiderzeugung mit der Bemerkung dar, dass die erzeugten Kohlensäuremengen dem 1 g Trockenmaterial der Wurzeln, bzw. der Bakterien entsprechen.

Tabelle Nr. I

Pflanze bzw. Bakterium	Kohlensäureerzeugung in 24 Stunden /CO_2 in mg/
Zuckerrüben	0,3 - 5,4
Gerste	63,2 - 74,6
Weizen	87,6 - 94,8
Roggen	100,7 - 131,0
Hafer	111,5 - 135,4
Buchweizen	212,5 - 274,0
Clostridium gelatinosum	480
Bact. Hartlebi	600
Azotobacter chroococcum	1270
Bacillus mesentericus	13000

Die Tabelle kann uns gleich darüber überzeugen, dass vom Gesichtspunkt der edaphischen Kohlendioxiderzeugung aus den Bakterien /und im allgemeinen die Mikroorganismen/ eine viel grössere Bedeutung haben, als die Wurzeln der Pflanzen. Und dass es trotzdem zwischen der Ausbildung der Wurzelkarrenkanäle und gewissen Pflanzenarten der Karstvegetation /z. B. Nardus stricta/ eine unverkennbare Verbindung gibt /P. JAKUCS 1956/, muss nach unserer Meinung mit der Erscheinung zusammenhängen, dass in der Wurzelzone der verschiedenen Pflanzen eine Bakterienpopulation unterschiedlicher Art und Anzahl lebt, ja sogar - z. T. in bezeichnender Beziehung damit - auch die Konzentration der lokalen Bodenfeuchtigkeit in der Rhizosphäre /vor allem zur Trockenzeit/ auf entsprechende Pflanzenarten verweist.

Inwieweit diese Verbindung zwischen den pflanzlichen Wurzeln und der im Boden vorliegenden Bakterienanzahl bedeutsam ist, konnten C. THOM und W. HUMFELD /1932/ bereits auch quantitativ bestimmen /Tabelle Nr. II/.

<u>Tabelle Nr. II</u>

	Anzahl der Bakterien in 1 g Boden	Anzahl der Pilze in 1 g Boden
im wurzellosem Boden	5 500 000	100 000
in der Rhizosphäre im allgemeinen	26 000 000	800 000
in unmittelbarer Nähe der Haarwurzeln	136 000 000	7 000 000

Da die Kohlendioxiderzeugung des Bodens weitgehend von der Menge seines Edaphons abhängig ist /FEHÉR 1954, GEIGER 1961, FEKETE 1952, 1958, STEFANOVITS 1963, FEKETE-HARGITAI-ZSOLDOS 1964, BECK 1968/, ist es auf Grund der oben gesagten fast zwangsläufig, dass es auch in der Kohlendioxiderzeugung der Böden von verschiedener Florabedecktheit /und folglich humushaltig/, sowie von unterschiedlichen Vegetationstypen grosse Unterschiede auftreten. Dass es wirklich so ist, wird durch die heute schon für klassisch angesehenen Beobachtungsangaben bestätigt. Einige von diesem werden in unserer Tabelle III dargestellt, mit der Bemerkung, dass sich die Beobachtungen zwar nicht auf Karsten beziehen, doch gehen auch auf den Karsten die gleichen Tendenzen vonstatten.

Beim Vergleich der vorher angeführten Tabellen I und II miteinander geht es gleich hervor, dass die auf dem Kalkgestein wirkende Korrosionsfähigkeit der Wurzeln gewisser Pflanzen /mit dem dazu gehörigen Phytoedaphon/ das vielfache gegenüber denjenigen Pflanzen sein wird, in demselben Landschaftsteil /z. B. in einer Doline/ leben, deren Rhizosphäre aber eine sowohl quantitativ als auch qualitativ unterschiedliche Bakteriensymbiosis verlangt. So können wir auf die Frage, die wir am Angang der vorliegenden Arbeit stellten, d. h. welche die kleinsten Ordnungseinheiten der physisch-geographischen Landschaft wären, bei denen die die Intensitätsstufen bewirkenden mikroklimagenetischen Differenzen noch in Form zum Ausdruck kommen dürften, nur die einzige Antwort geben, dass es solche kleinsten Grössenordnungen durchaus nicht gibt.

Tabelle Nr. III

Kohlendioxiderzeugung einzelner Bodenarten

/nach STOKLASA-ERNEST/

Bodenart	Tiefe	CO_2-Erzeugung von 1 kg bei 20°C in 24 Studen in mg.
Lehm	Oberboden	49,7
Lehm	Unterboden	7,6
kalkhaltiger Boden	Oberboden	18,5
kalkhaltiger Boden	Unterboden	9,8
Moorboden	Oberboden	41,2
Waldboden	Oberboden	36,4
Waldboden /humusarm/	25 cm	9 - 12
Waldboden /humusreich/	25 cm	20 - 26
Weide	25 cm	10 - 116
unfruchtbarer, humusarmer Boden	25 cm	8 - 14
guter Roggen- und Weizenboden	25 cm	30 - 48
guter Kleeboden	25 cm	53 - 60

Und zwar gibt es solche darum nicht, weil bei der Verkarstung unterhalb des Bodens, wo die sonst die Arealität gewährenden üblichen oberflächlichen Planationsvorgänge /Wind-, Wassererosion usw./ nicht zur Geltung kommen können, noch auch innerhalb des kleinsten Landschaftsteils unzählige winzige Flecken von unterschiedlicher

Denudationsdynamik in unmittelbarem Nebeneinander vorhanden sind. Diese haben eine Grössenordnung manchmal von einem Quadratmeter, andersmal Quadratdezimeter oder sogar Quadratmillimeter. In diesen sich nach den Unterschieden des Korrosionsgrades differenzierenden Kleinsträumen manchmal sogar von infinitesimalem Masse entwickeln sich eigenartige entsprechende Lösungsmikroformen, die in ihrer Gesamtheit dann die herkömmlichen Formentypen der Karstmorphologie gestalten, so wie das Karrenfeld, die Doline usw. sind.

Es wäre natürlich vollständig verfehlt, aus all diesem eine Folgerung zu ziehen, als wenn die Ausbildung, Gepräge und Anordnung der Mikroformen an einem Karst und nur durch die statistische Summierung der Teilvorgänge der Makrofazies enstehen sollte. In der Tat wirkt nämlich die reversibile Bedingtheit auch im umgekehrten Sinne: das zonale Makroklima der Landschaft, ihr lithologisches Gepräge, ihre topographischen, tektonischen, hydrographischen usw. Varianzen bestimmen die Merkmale des Mikroklimas und der Assoziationseinheiten, die Verhältnisse und Anordnungen ihrer vorkommenden Typen. Das heisst, die Anfangsprozesse selbst gehen zwar in den Mosaiken der Mikroräume vor sich, aber diese Mosaiken passen sich in ein oder mehrere grössere Systeme ein, für die Grundzüge /dessen oder/ derer Systeme aber nicht mehr die mathematische Summierung der Teilprozesse der Mosaiken bezeichnend ist.

Untersuchungsmethodik des CO_2-Gehalts des Gasgemenges der Mikrobodenräume

Wir haben erfahren, dass die, unsere Probleme am meisten annähernden Untersuchungen nicht von den Forschungsthemen der Geomorphologen, noch weniger der Karstmorphologen herrühren, sondern in erster Linie landwirtschaftliche, bzw. pedologische und biologische Ansätze haben. Es ist also natürlich, dass sich auch die Angaben nicht auf die ungestörten Böden- und Vegetationsvorgänge, auf deren CO_2-erzeugende Korrektionen beziehen, sondern vor allem auf Nutzpflanzen konkretisiert sind. Auch manche in der karstgenetischen Literatur vorkommenden Hinweise /TROMBE 1951/2, 1952, 1956, SMYK-DRYZAL 1964, usw./ gründen sich nur auf einigen Messungen, oder aber verallgemeinern die von anderen Pedofazies stammenden Beobachtungen der bodenkundlichen Literatur. Und obwohl das Stützen auf diese Analogie - bis wir uns nicht auf konkrete Messungsreihen im Gelände verlassen können - von sich selbst versteht, ja sogar annähernd gute Ergebnisse liefern kann, mussten wird doch danach streben, das Problem auf Grund der sich selbst auf das Problem beziehenden Forschungen beantworten zu können.

Das war aber keine leichte Aufgabe und unsere angesetzten Untersuchungsreihen sind noch bei weitem nicht beendet. Eine besondere Schwierigkeit bereitete vor allem, dass wir uns gezwungen sahen, selbst auch die entsprechende Forschungsmethodik zu finden. Die gegenwärtig gebräuchlichen die Bodenatmung registrierenden und die Analysis der Bodanatmosphäre ermöglichenden Methoden waren nämlich in unserem Falle nicht zweckmässig.

Wie bekannt, erfolgt die Bestimmung des CO_2-Anteils der Bodenluft im allgemeinen derartig, dass man aus dem ungestörten Boden mit Hilfe entsprechender Einrichtung /meist mit einem scharfkantigen Metallzylinder von 1 l Rauminhalt/ eine Probe nimmt, dann verdrängt man aus der mit dem Ausschliessen des Luftaustausches ins Labor transportierten Probe mit Wasser oder mit einer Salzlösung von 10 % die Bodenluft und sammelt mit einem Trichter die Luftblasen. Die so ausgewonnene Bodenluft wird dann im Rauchanalysierenden ORSAT-Gerät durch Absorbieren von Kalilauglösung oder durch die Bariumhydroxid-Methode /Titration mit Salzsäre/ von GORBUNOV auf CO_2-Gehalt untersucht /BOROJEW-JEGOROW-KISELJEW 1951, di GIÉRIA-KLIMES-SMYK-DVORACSEK 1957, BALLENEGGER-di GIÉRIA 1962/.

Wenn man das Mass der Kohlendioxiderzeugung des Bodens in der Zeiteinheit feststellen will, so wird sich der Gang der Untersuchung insofern verändern, dass man im Labor durch die Bodenproben mit langsamer Strömung Luft durchfliessen lässt, deren Kohlendioxid-Anteil sowohl beim Eintritt, als auch beim Austritt gemessen /auf Absorptionswege, durch Volumen- oder Gewichtanalyse, bzw. Titrieranalyse/ und den Unterschied der beiden in CO_2-Gehalt umgerechnet, auf die Menge und die Messungszeit des im Versuch verwendeten Bodens bezogen wird.

Nach einem anderen Verfahren drückt man in den Boden eine für diesen Zweck ausgebildete, seitens und oben geschlossene Metallglocke, in der die unter natürlichen Bedingungen ausgeatmete Luft aufgefangen wird, dann wird die Glocke mit einem entsprechenden Gerät /z. B. LUNDEGARDH-Gerät/ in Verbindung gebracht, und die durch $Ba/OH/_2$ absorbierte CO_2 Menge mit Hilfe der bereits erwähnten Salzsäure-Titrationsmethode errechnet /BALLENEGGER 1953, FEHÉR 1954/.

Wir haben unsere ersten Untersuchungen üben den CO_2-Gehalt der Böden an der Karstoberfläche auch mit Hilfe der oben angeführten Methode durchgeführt, aber wir wurden im Laufe der Erfahrungen wegen des grossen Zeit- und Laboraufwandes der erwähnten Verfahren dazu gezwungen, eine raschere und am Standort durchführbare Messmethode auszuarbeiten. Das wurde sonst über dem Streben nach besserem Zeitaufwand hinaus auch von anderen Gesichtspunkten aus begründet. Wir haben nämlich beobachtet, dass es hinsichtlich des CO_2-Gehaltes der Bodenluft nicht gleichgültig ist, wieviel Zeit von der Probenentnahme an bis zum Beginn der Bearbeitungen im Labor vergeht. Von den gleichzeitig und an benachbarten Stellen, unterhalb einer einheitlichen Vegetation entnommenen Bodenproben von gleicher Beschaffenheit haben wir immer in derjenigen einen erheblich höheren CO_2-Gehalt gefunden, deren Luftverdrängung wir erst später begonnen haben. Das ist sonst verständlich, denn in der hermetisch geschlossenen Bodenprobe wird das Aufhören der biovegetativen und anderen Oxidationsvorgänge ja durch nichts bis zum Vorliegen eines ausreichenden atmosphärischen Sauerstoffvorrats begründet. Und bei massenhaften Untersuchungen, wobei das wichtigste gerade im Vergleich liegt, bedeutet dieser Umstand beinahe die Unnutzbarkeit der Methode.

Und wollten wir das Ausmass der Bodenatmung messen, vermehrten sich die Probleme weiter. Eine derartige Ermittlung ist nämlich, wie das aus der Natur der Sache folgt, so zeitaufwendig /nach der angewandten Methode brauchman mindestens 5 bis 10 Stunden Beobachtungszeit im Labor oder im Gelände zur Aufnahme einer einzigen Angabe/, dass wir nicht einmal auf diese Weise statistisch auswertbare Datenreihen gewinnen konnten.

Nachdem wir im Sinne unserer Zielsetzung das Ausmass des CO_2-Gehaltes der Bodenräume an benachbarten Karstoberflächen von unterschiedlichem Mikroklima vor allem in ihrer Gleichzeitigkeit vergleichen mussten, wurde es wirklich unvermeidlich, eine schenelle und am Standort durchführbare Messmethode zu experimentieren. Zu diesem Zweck haben wir zwei Verfahren ausgearbeitet, deren kurze Beschreibung wir - aus Mangel an einer früheren entsprechenden Publikation - im folgenden angeben.

<u>Methode I</u>. Das Ansaugen der Bodengase erfolgt durch eine dünne Messingsonde mit einem Durchmesser von 5 mm und am Ende mit perforierter Wand, die in den gewünschten Bodenhorizont einfach einzustechen ist. Es ist zu bemerken, dass das untere Ende der ungerfähr 40 cm langen Sonde in einer Konusspitze endet und ein - dem Durchmesser des Rohrinnern gleich dicker- Stahlstab darin eingebracht werden kann. Diesen Stab lassen wir bei seinem Eindrücken in den Boden in der

Sonde liegen und erst vor dem Ansaugen der Probe soll er daraus gezogen werden. Der spaltenfrei anpassende Stahleinsatz dient einmal zur Versteifung des dünnwandigen Rohres während seiner Einführung in den Boden, zum anderen um zu vermeiden, dass die Bodenkörnchen durch die Öffnungen in die Sonde gelangen, insbesondere aber die vorzeitige Ausströmung der Bodenluft und die Möglichkeit der Beimengung von fremder Luft auszuschalten.

Anschliessend an das Einstechen der Sonde machen wir die Bodenoberfläche in einigen dm^2 Flächen ringsum des Stichpunktes luftundurchdringlich, was z. B. durch den Aufsatz eines dichten Ölfilms /z. B. gebrauchten Öls/ erfolgen kann. /Bei sehr porosen, krumeligen Boden ist es zweckmässigerer, geschmolzenes Paraffin oder Stearin anzuwenden./ Wir lassen die Bodenluft durch einen für diesen Zweck hergestellte und an das über dem Böden befindliche Sondenende anschliessende, durch Feder oder Schwachstrom /Taschenlampenbatterie ernährten/ Motor ansaugen und führen in den an die Luftaustrittstelle angeschlossenen Gummiballon /eventuell in eine Ballblase/ /Abb. 5./.

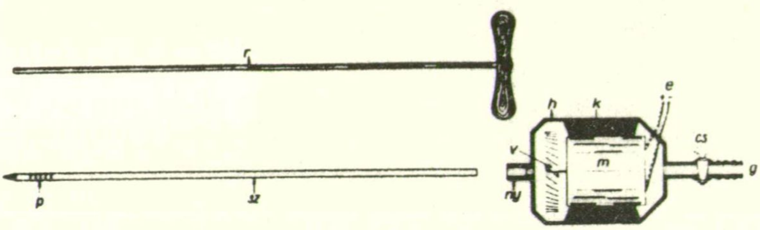

Abbildung 5. Prinzip der Bodensonde zum Ansaugen der Bodengase /original/.

sz = dünnwandiges Sondenrohr zum Gasansaugen,
p = Perforation in der Rohrwand,
ny = luftdichte Anschlussmuffe des Pumpenkörpers,
v = Luftturbinenrad mit 16 Schaufeln,
m = Schwachstrommotor /12 V/ /z. B. Motor des Scheibenwischers des Kraftwagens/,
k = motorhaltende Konsolen,
e = luftdichte isolierte Anschlusstellen der Energiezuführungsleitungen,
h = Decke des Pumpenhauses,
cs = Sperrhahn,
g = Anschlusstelle des Gummischlauchs,
3 = Versteifungsgestänge.

Nach der Entnahme von etwa anderthalb dl Menge Bodenluft /sie wird abhängig von der Luftdurchdringlichkeit des Bodens in 10 bis 150 Minuten ausgeschieden/ schliessen wir den Gummischlauch an die durch eine Druckpinzette verschlossene ORSAT-Gerät an, die wir mit der ersten Lufterfüllung durchspülen, dann titrieren wir die zweite

Gaserfüllung durch eine Kalilauge-Absorptionslösung auf Gasvolumen.

Durch die Methode, die wir 1965 zuerst angewendet haben, kann eine Person je Stunde 4 bis 5 Untersuchungen am Standort durchführen. Wollen wir die Messung an einem späteren Zeitpunkt /z. B. am nächsten Tage/ wiederholen, ist es zweckmässig mit mehreren Sonden zu arbeiten und die eingesetzte Sonde zur Zeit der Wiederholungen im Boden liegen lassen.

In den Jahren 1955 und 1956 haben wir mit diesem Verfahren in fast sämtlichen Karstgebirgsteilen Ungarns /Nord-Borsoder Karst, Bükk, Pilis, Gerecse, Bakony, Mecsek, ja sogar im Soproner Becken: in Fertőrákos/ auch Serienmessungen durchgeführt. Auf Grund der Aufnahme von 300 Beobachtungen mussten wir sehen, dass obwohl die CO_2-Sättigung der Porengase der einzelnen Böden und Horizonte manchmal auch innerhalb kleiner Abstände bedeutsame /von mehreren Prozenten/ Unterschiede vorliegen, ja sogar auch der Bodenluftraum an der gleichen Beobachtungsstelle Veränderungen von grosser Amplitude /in Abhängigkeit der Tageszeit und anderer Faktoren/, manchmal recht schnelle Konzentrationsveränderungen haben, liefern unsere Angaben zur Ermittlung der Regelmässigkeiten,noch immer nicht hinreichende Kenntnisse.

Was die Ursache betrifft, dachten wir daran, dass die Beimischung der im Luftpumpengehäuse vorhandenen natürlichen Luft die Genauigkeit der Ergebnisse stören kann. Das war zweifellos ein ergebnismodifizierender Umstand, aber das ist gleichzeitig auch wahr, dass zu jeder Probe der gleiche Anteil /etwa 30 mm/ Normalluft beigemengt wurde, so wurden also nur die Werte von absoluter Grösse und nicht die Proportionen modifiziert.

Der Anspruch auf Vervollständigung der Methode war aben auch von einer anderen Seite her begründet. Das zur Analyse unvermeidlich notwendige etwa 150 ml Bodengas schieden sich in der depressiven Linse mit verschiedenem Durchmesser aus dem das perforierte Sondenende umgebenden Boden aus, und die Ausdehnung und Form dieser Linse waren von den Porositätskennwerten, von Feuchtigkeitsgehalt usw. abhängig, d. h. sie bildeten einen unbekannten Faktor. Deswegen war vor allem die spezifische CO_2-Erzeugung der Rhizosphären der benachbarten Pflanzenarten durch unsere Methode nicht erfolgreich zu untersuchen.

Um die oben angeführten Probleme zu überwinden, mussten wir also eine Methodik für Mikroanalysis ausarbeiten, wodurch die genaue Analysis sogar von wesentlich geringfügiger Gasmenge durchgeführt werden kann. In diesem Falle kann nämlich die am vorgesehenen Standort orientierte Gewinnung des geringfügigen Gases schon viel besser gewährleistet werden. Die Lösung dazu haben wir 1967 durch unten das dargestellten Verfahren Nr. II gefunden.

<u>Methode II</u>. Die Menge der zur Analyse notwendigen Bodenluftprobe ist insgesamt etwa 5 ml. Man entnimmt diese Gasmenge mit der PRAVAZ-Spitze vom beliebigen Punkt des Bodens. /Es ist angebracht, die vollständige Abdichtung des Kolbens der Spritze oben durch Paraffinölung zu übersichern!/ Nach dem Einstechen der Injektionsspritze, deren Länge der zu untersuchenden Bodentiefe entsprechend gewält wurde, scheint es auch hier zweckmässig zu sein, die Bodenoberfläche in einem mit etwa 20 cm, Durchmesser Flecken

abzudichten. Es ist noch zu bemerken, dass beim Einsetzen der Spritze in den Boden, der Mandrin darin stecken bleiben soll, den wir erst unmittelbar von dem Anschliessen an die Spritze zurückziehen.

Das Ansaugen von 5 ml Bodenluft - wenn nur der Boden nicht ausgesprochen undurchlässiger Ton oder nicht staunässig ist - bereitet nach unseren Erfahrungen im allgemeinen keine Schwierigkeit und auch der Durchmesser der herbeigeführten Gasdepressionslinse beträgt nicht mehr als einige cm. So ist das Ansaugen den durch die Zielsetzung bestimmten Wünschen völlig entsprechend, es lokalisiert sich auf eine gut zu bezeichnende Bodensphäre /z. B. auf die Wurzelzone eines einzigen Grashaufen/.

Die entnommene Luftprobe wird mit der in Abb. 7. dargestellten Apparatur durchgeführt wie folgt.

In das durch einen breit durchbohrten Glasschliffhahn /B/ in zwei Teile /A und C/ gegliederte Reagenzglas /den D Gummistopfen entfernt/ giesst man Kalilauglösung bei geöffnetem Hahn derart, dass sie in den A-Teil und das Bohrloch des Gasstopfens luftblasenfrei erfüllt. /Verdünnungsverhältnis: 1 Teil KOH, 2 Teile H_2O./ Nach Abschliessen des Sperrhahns wird die im C-Teil übriggebliebene Kalilauge ausgegossen und dieser Gefässteil nach Durchwaschung unter mehrmaliger sorgfältiger Abspülung entlaugt. Den C-Teil des auf solche Weise vorbereiteten Reagenzglases mit einer zweckmässig rot oder dunkelblau gefärbten 10 % NaCl-Lösung völlig erfüllt, stellt man, die Öffnung nach unten, in eine die gleiche Lösung enthaltende flache Glaswanne. In dieser Lage lässt man darin aus dem Gasgehalt der PRAVAZ-Spritze von unter her soweit Gas aufbrausen, bis das Gas die gefärbte Lösung bis zum an der Seite der C. Gefässteils angebrachten

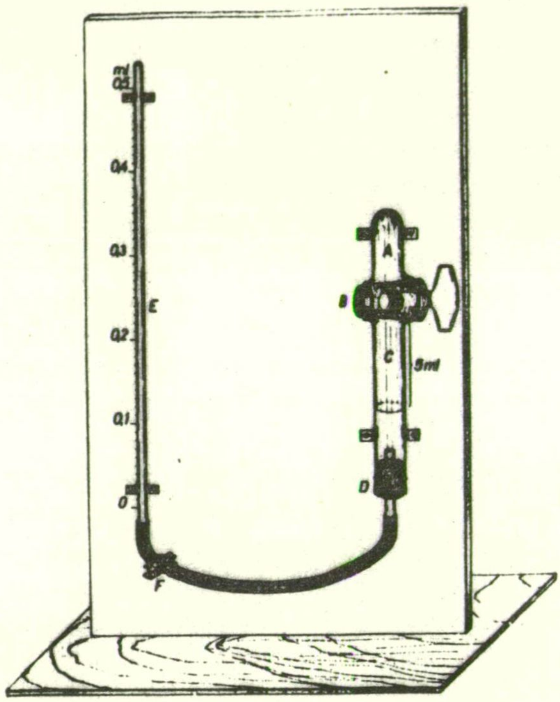

Abb. 7. Prinzip des Mikro-Gasanalysators mit Kapillarrohrregister /original/

A = Kalilauge-Reservoir, B = Glasschliffhahn mit breitem Bohrloch, C = aus einem 5 ml kalibrierten Oberteil und einem unkalibrierten Halsteil mit Stopfeneinsatz bestehenden Reagenzkammer, D = einwegiger Gummistopfen mit Glasrohreinlage und Ausleitungsanschluss an den Verbindungsgummischlauch, E = am oberen Ende offenes Kapillarrohr mit Skala für das Ablesen der Beobachtungen F = Klemme

5 ml-Strich verdrängt. Danach stopft man das Reagenzglas - dessen Mündung noch immer unter dem Flüssigkeitsspiegel haltend - mit dem D Gummistepfen ein.

Es sei bemerkt, dass das Innere des Bohrlochs im Gummistopfen, sowie des zu dem mit Skalaeinteilung versehenen Kapillarrohr /E/ Anschluss gewährenden Glas- bzw. Gummischlauch auch mit der erwähnten NaCl Farblösung gefüllt werden soll.

Nach Durchführung des Anschlusses der beiden Teile der Einrichtung befestigen wir unsere Apparatur - von aussen her abgetrocknet - auf ein entsprechendes Gestell in der Abb. 7 dargestellten Lage, dann den F Sperrhahn geöffnet, drücken wir den D Gummistopfen ein wenig mehr hinein, damit der dadurch im C-Raum entstandene schwache Überdruck in einem E Rohr eine Flüssigkeitsfaden voll hinauftreibt. Den am oberen Ende eventuell auftretenden Überlauf trocknet man mit Löschpapier ab und nachdem im Kapillarrohr das obere Ende des Flüssigkeitsfadens stillgestanden hat /das kann manchmal wegen der temperaturbedingten Volumenausgleich sogar 1 bis 2 Minuten in Anspruch nehmen/, notieren wir dessen Maniskus. Nun wird der H Hahn so gestellt, dass die Verbindung zwischen A und C Räume hergestellt ist. Die Kalilaugelösung fliesst vom Raum A zum Raum C hin, und vom C wandert das Gas z. T. zum A über. Inzwischen wird der CO_2-Komponent der Gasmenge absorbiert. D. H. nun wird das Volumen der in den Gefässteilen A + C befindlichen sämtlichen gasförmigen und flüssigen Zustandsphasen im Verhältnis zum Gesamtvolumen des vor dem Öffnen des Hahnes separeten A + C Raumes genau um den Gasvolumen-Anteil des CO_2-Komponenten der Gasmenge geringer. Dem Aufhören des CO_2 Partialdruckes entsprechend sinkt also der Flüssigkeitsspiegel im Kapillarrohr ab.

Wenden wir nun ein Kapillarglas an, bei dem 0,5 ml Flüssigkeit in 50 cm Länge den inneren Raum des Rohres erfüllt, wird jedem Prozent CO_2 ein Absinken von 5 cm des Meniskus entsprechen. In diesem Falle also, da eine Meniskussenkung von halb mm noch beobachtbar ist, wir unsere Apparatur mit 0,01 % Empfindlichkeit für die Messung eines maximalen Kohlensäuregehaltes von 10 % zum unmittelbaren Ablesen jeder Zwischenstufe geeignet. Man kann natürlich je nach dem Kaliber und der Länge des Kapillarrohrs ein mehr oder weniger empfindliche Beobachtungsskala anfertigen.

Bei Durchführung der Messungen muss man doch einem einzigen Gesichtspunkt besondere Aufmerksamkeit schenken: Die Einrichtung reagiert empfindlich auch auf die kleinste Temperaturveränderung. Deswegen darf man damit nur im Schatten arbeiten und man muss den die Reagenten enthaltenden Gefässteil nur mit einer Holzpinzette angreifen, vor der Hand- und Atmungswärme schützen.

Die Anwendung unseres Verfahrens ergibt bei hinreichender Übung sehr schnelle und genaue Ergebnisse. Mit Hilfe dieses Verfahrens haben wir in 1967 und 1968 etwa 940 Messungen zum kleineren Teil in den ungarischen, zum grösseren in jugoslawischen Karstgebieten durchgeführt. Über deren Ergebnisse, mit Rücksicht darauf, dass unsere Forschungen in diesem Themenkreis erst nach Erfüllung eines weiteren mehrjährigen Aufgabenprogramms zu Ende gebracht werden, geben wir im vorliegenden Aufsatz keine ausführliche Rechenschaft. Doch müssen wir auf einige, heute schon als abgeschlossen zu betrachtende Teilfragen bereits eingehen, da unsere Ergebnisse zum Verständnis der in den Mikroräumen vor sich gehenden Karstkorrosionsvorgänge wichtige Gesichtspunkte liefern.

Beispiele für die Merkmale des CO_2-Haushalhaltes in Bodendenatmosphären der karstigen Mikroräume mit unterschiedlichen biologischen und klimatischen Besonderheiten

Schon bei unseren ersten Bodenluftuntersuchungen konnten wir uns darüber überzeugen, dass auf die CO_2-Konzentration der Bodengase bezogen nicht nur die gleichzeitigen und an verschiedenen Stellen durchgeführten Beobachtungen erhebliche Abweichungen in der Grössenordnung zeigen, sondern sogar an derselben Probenentnahmestelle beträchtliche substantielle Differenzen bei der Analyse der in unterschiedlichen Zeitpunkten entnommenen Proben auftreten können. Und zwar, handelt es sich hier nicht nur um die in der pedologischen Fachliteratur /z. B. D. FEHÉR 1954/ erörterten, an Jahreszeiten gebunden veränderlichen Konzentrationswandlungen in langer Amplitude, sondern um Proportionsmodifikationen der Gaszusammensetzung in viel kürzeren Perioden und von Bedeutung. In den meisten fällen kann man nämlich zweimal die gleichen Messergebnisse nicht einmal an derselben Stelle beobachten.+/

Die oben angeführten haben uns also gezwungen, uns nicht mit dem zahlreichen, doch sporadischen Angaben zu befriedigen, sondern einmal nach dem Vergleich von homochro-

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+/ Es ist hier zu bemerken, dass es nach unseren Erfahrungen zweckmässig scheint, zwischen zwei nachfolgenden Beobachtungen - bei Anwendung der 5 ml mikroanalytischen Methode - eine Ruhepause von mindestens einer Stunde für die Gasregeneration zu gewähren.

nen, womöglichst vom gesamten Gebiet gewisser. Karstformen /z. B. Dolinen/ entnommenen Datenreihen zu streben, zum anderen ein Übersichtsmaterial zu sammeln, an dem sich die Entwicklungstendenzen in mehr oder weniger langes Zeitfolgen einer ausgewählten Beobachtungsstelle widerspiegeln. Deshalb haben wir - insbesondere im Jahr 1968 - Messungsreihen zumeist ganz - oder mehrtägigen Perioden hindurch durchgeführt, wobei die Kontinuität durch eine Beobachtunsgdichte von 2 Stunden, in nötigem Falle sogar von 1 Stunde gesichert wurde.

Diese Untersuchungen führten zu ausserordentlich aufschlussreichen, grundsätzlich bedeutsamen Erfahrungen unter anderem in Jugoslawien, in einer Doline des südlich der Stadt Karlovac in Kroatien gelegenen flachen, mit Terra Rossa bedeckten Plateaus. Hier haben wir in den Boden sowohl der N-, als auch der S-exponierten Dolinenhang 2 Nadelsonden eingesetzt, und zwar je eine in 5 cm Bodentiefe und je eine in die 20 cm tiefe Zone. Es ist zu bemerken, dass die ganze Doline von einer ziemlich homogenen Vegetation bedeckt war: der ungefähr 60 bis 80 cm hohe Adlerfarn /Pteridium aquilinum/. Für die Stationen haben wir in beiden Expositionen Oberflächen mit gleicher Hangneigung /etwa 20°/ gewählt und die Probenentnahmenadel unter je ein Pteridium gestochen. Makroskopisch erkennbare Unterschiede der Bodenzusammensetzung haben wir hinsichtlich der Expositionen nicht beobachtet, nur dass der Boden in der N-Exposition /bereits in der 5 cm Tiefe/ wesentlich feuchter war. Wegen Mangel an quantitativen Messungsmöglichkeiten können wir uns hinsichtlich der letzteren nur auf Schätzungen beschränken./

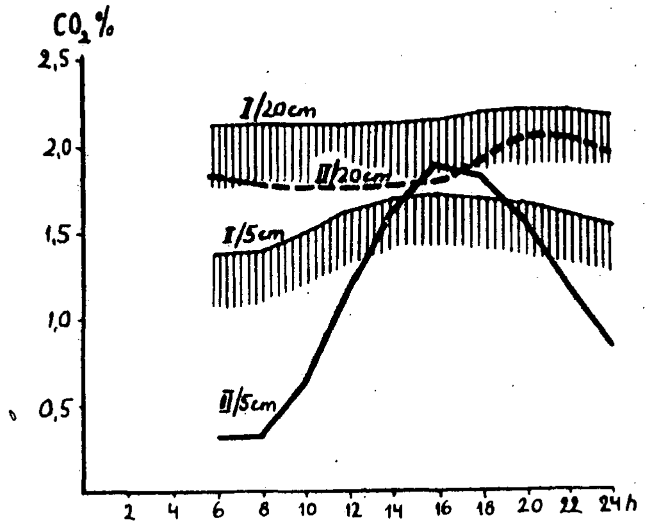

Abb. 8. Veränderungen im Laufe von 18 Stunden des CO_2-Gehaltes der Bodenluft, entnommen von den 5 und 20 cm Horizonten unter einem gut entwickelten Pteridium aquilinum an einem klaren, windstillen Sommertag /14. 7. 1968/. Die Aufnahmereihe wurde in einer Doline Kroatiens /etwa 12 km weit südlich von Karlovac entfernt an der nach Plitvice verlaufenden Landstrasse /gelegenen/ an N- /I/ und S-exponierten /II/, ca. 20° geneigten Hängen, auf Grund einer Beobachtungsdichte von 2 Stunden. Bodenart: 20 cm vorherrschend rotlehmiger Rendzina, im 5 cm Horizont mullförmiger humoser Oberboden mit Krumelgefüge /original/.

Am ersten Untersuchungstag /14. 7. 1968/, wobei es den ganzen Tag hindurch warm, klar und windstill war, sind die Veränderungen des CO_2-Gehaltes der Bodengase in Abb. 8. dargestellt.

Aus den auf die einzelnen Punkte und Horizonte bezogenen täglichen Konzentrationskurven ergeben sich die nachstehenden Feststellungen, die - da bisher keine Messergebnisse entgegengesetzten Sinnes von anderswo erhalten sind - vielleicht bereits jetzt in verallgemeinterer Form abgefasst werden können.

1. Der CO_2-Gehalt der Bodenluft hat - an den mit Vegetation bedeckten Karstoberflächen - in den untersuchten Expositionen und bis zur untersuchten 20 cm Tiefe in jeder Schicht einen Tagesgang, der sich der Wärmemengenkurve des Bodens empfindlich und in annähernd geradem Verhältnis anpasst.

2. In der S-Exposition sowohl im Bodenhorizont von 5 cm, als auch in dem von 20 cm schwankt die Konzentration des Gases mit extremeren Amplituden, als in den N-Expositionen.

3. In beiden Untersuchungsschichten des Oberbodens bleibt der CO_2-Anteil der Gasmenge - hinsichtlich des Tagesdurchschnitts - unter dem der N-Exposition. /Wie wir später sehen werden, trifft dieser Punkt nur dann zu, wenn der Boden in der Südexposition trocken, während in der Nordexposition feuchter ist./

4. In der 20 cm Bodenzone ist die Gaskonzentration meistens höher, als in der 5 cm Zone. /Im späteren werden wird wird auch in bezug auf diesen Satz beweisen, dass er nur in dem Falle zutrifft, wenn die obere Bodensphäre wesentlich trockener ist, als die darunter liegende./

Das Wesen der im Punkt 1. einerseits und in den Punktten 3. und 4. andrerseits gezogenen Folgerungen miteinander vergleichen soll die Abfassung der vorstehenden Ansprachen ohne Zweifel eine Art Antagonismus enthalten. Denn, wenn der CO_2-Anteil der Bodenluft mit der Wärmemenge tatsächlich im Zusammenhang des geraden Verhältnisses steht, können wir mit Recht erwarten, dass auch die CO_2-Konzentration des Bodengases an den S-exponierten, einen höheren Betrag von Isolationskalorie anhabenden Hängen, ferner in den sich stärker erwärmenden 5 cm-Bodenzonen ausgeprägter wird. Im gegebenen Falle müssen aber auch zwei Bedingungen beachtet werden, die die biostimulative Wirkung der Wärmemenge bzw. deren reale Widerspiegelung am Anteil des Kohlendioxidgehaltes zerstören. Diese sind einmal die erhebliche Trockenlegung des Bodens der S-exponierten Hänge, zum anderen die mit seiner Trockenlegung im Zusammenhang stehende erhöhte Durchlüftung.

Dass die in der biogenetischen Aktivität /in übertragenem Sinne der CO_2-Erzeugung/ des Edaphons gespielte Rolle der Bodenfeuchtigkeit durchaus nicht vernachlässigt werden kann, haben wir bereits in Abbildung 4 dargestellt. Welche erhebliche Bedeutung doch in der Beurteilung der Frage dem Durchlüftungsgrad des Porenraumes des Bodens zugeschrieben werden soll, deren Ansprache wurde erst durch die an den folgenden Tagen in der untersuchten Doline Kroatiens aufgenommenen Diagramme ermöglicht. Denn am fraglichen Tag hat die vorherige Windstille aufgehört und die sanften Windstösse übten auf die Gestaltung der Kurven eine sehr beachtenswerte Wirkung aus /s. Abb. 9/ Diese Wirkungen können im wesentlichen wie folgt zusammengefasst werden.

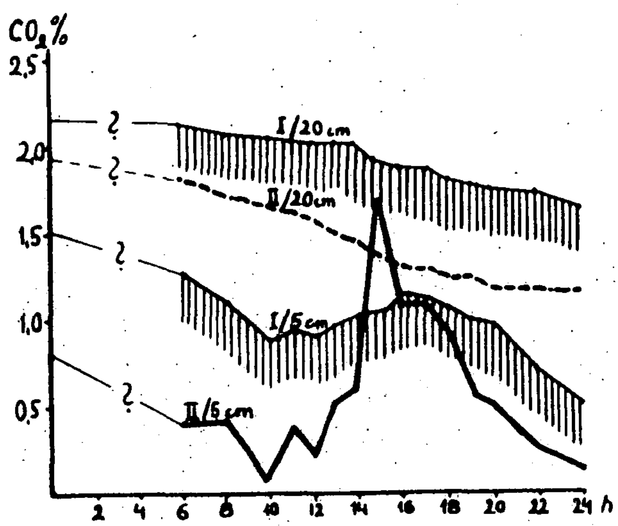

Abb. 9. Veränderungen des CO_2-Gehaltes der Bodenluft an den im Text der vorangehenden Abbildung bereits erwähnten Untersuchungsstellen an einem etwa 60 % klaren und von den Vormittagsstunden an eingesetzten windigen Sommertag /15. 7. 1968/ im Zeitraum von 6 bis 24 Uhr /original/.

1. Bereits bei schwacher Windgeschwindigkeit nimmt der CO_2-Gehalt der Bodenluft stark ab.

2. Diese Abnahme der Gaskonzentration hängt nicht mit dem Verlangsamen der CO_2-Erzeugung im Boden, sondern mit der Erhöhung des gegebenen Gasvorrats, der Austauschdynamik des Porenluftraumes zusammen. /Darauf kann man schliessen z. B. aus dem Höchstwert der Kurve II/15 von 15 Stunden, dessen

in einer kürzeren Windstille ohne Übergang eingesetzte Bildung erst dann verständlich wird, wenn man annimmt, dass sich die biologische Aktivität des Edaphons in den niedrige Werte verzeichnenden Zeitdauern der früheren Stunden sukzessive erhöhte, aber die Voraussetzungen des in loco nascendi Erhaltens der entstandenen gasförmigen Stoffwechselprodukte erst jetzt angegeben wurden. Wir müssen sogar annehmen, dass selbst die aeroben Vorgänge im Boden von den durch den verursachten Luftdurchwaschungen noch günstig beeinflusst werden, und damit werden von der Wirkung der Windstösse wirklich nur die Bedingungen der Gaskonzentration schädlich betroffen.

3. Je feuchter der Boden ist, ist der Gasaustausch durch den Wind ein desto langsamer und mit geringerer Wirksamkeit sich vollziehender Vorgang. Das tritt besonders gut zu Erscheinung beim Vergleich der Diagramme II/5 und I/5. Die so entstandenen Wertunterschiede ergeben wieder dass der CO_2-Gehalt der Bodenluft der N-Expositionen auch jetzt in beiden untersuchten Zonen eine höhere durchschnittliche Konzentration hat im Vergleich zu denen der S-exponierten Böden.

4. Die verhältnismässig bedeutsamen doch kurz andauernden Gaskonzentrationserhöhungen des obersten Bodenhorizontes beeinflussen praktisch nicht die Gasmengenentwicklung von abnehmender Tendenz in windigem Wetter der tieferen Horizonte.

Die angefangene Untersuchungsreihe in Kroatien weiter zu führen, wurde durch einen in der Nacht auf den 16-ten Juli erfolgten ergiebigen Niederschlagsfall begründet. Sonst zeigte der CO_2-Haushalt der Bodenluft sowohl während des

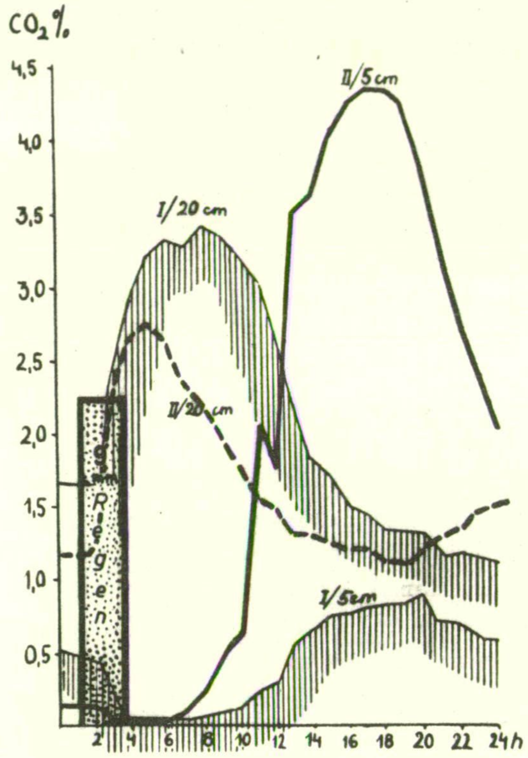

Abb. 10. CO_2-Gehaltsveränderungen der Bodenluft der in den vorhergehenden Abbildungen angedeuteten Untersuchungsstellen in Kroatien, an einem klaren, windstillen Sommertag, der einem Nachtsturm mit 9 mm Regen folgte /16. 7. 1968/. Der Regen, der von 1^h 10 bis 3^h 35 dauerte, war am Anfang intensiv, dann folgten in Wellen aufeinander die sich später noch mehrmals wiederholenden, aber schwacheren Niederschläge mit geringfügigeren Spenden /original/.

Regens, als auch in den nachfolgenden Stunden ausserordentlich interessante Gänge so in der 5 cm, wie in der 20 cm-Bodentiefe. Die erhaltenen Datenreihen sind in den Vergleichsdiagrammen der Abb. 10 zusammengefasst, woraus die nachstehenden Folgen zu ziehen, liegt völlig auf der Hand.

1. Der Niederschlag absorbiert in derjenigen obersten Bodenzone, die von seinem versickernden Anteil unmittelbar durchfeuchtet wird /in unserem Falle war die 5 cm-Bodenzone sowohl in der N-, als auch in der S-Exposition/, den Kohlendioxidvorrat des Bodenluftraumes im wesentlichen bereits im Laufe der Versickerung, d. h. verzehrt ihn praktisch fast völlig.

In den tieferen und von der Versickerung unmittelbar nicht betroffenen Bodenhorizonten fängt der CO_2-Anteil der Porengase gleich nach dem Niederschlagsfall, sprunghaft zunehmen und es entwickeln sich, im Vergleich zu den früheren Werten ungewöhnlich hohe Konzentrationswerte. Hier kommt also ein überraschender <u>Umkehrung</u> des CO_2-Haushaltes der 5 und 20 cm-Bodenhorizonte zustande, die dann wesentlich auch in den späteren Tageszeiten erhalten bleibt /falls eine starke Erwärmung durch Insolation in den Tagesstunden erfolgt/.

Was die Ursache der auffallenden nächtlichen Erscheinung betrifft, können wir nur daran denken, dass die infolge des Regens erfolgte starke Quellung der oberen Bodenschicht und die damit zusammenhängende Luftundurchdringlichkeit die frühere natürliche Durchlüftung der tieferen Bodenhorizonte verhindert, und so werden die Gasprodukte der dort vor sich gehenenden Stoffwechselvorgänge durch Moder und sonstige Oxidation angehäuft.

Dass dieser Faktor wirklich die Hauptursache der Erscheinung sein kann, das ergibt sich wohl aus dem Unterschied zwischen den 20 cm-Diagrammen der S- und N-Expositionen. Bei der vor dem Regenfall einen trockeneren Boden aufweisenden S-Exposition /Kurve II/20/ hört nämlich durch die Durchfeuchtung erfolgte Luftabdichtung früher auf /bereits nach 5 Uhr in der Früh/, als im Falle des von vornherein feuchtiger und so bei gleichem Durchfeuchtungsgrad dauerhfter ertrunkenen N-exponierten Bodens /Kurve I/20/, wobei die Abnahme der Gaskonzentration wesentlich erst am Morgen nach 8 Uhr einsetzen kann.

3. Unter Wirkung der indirekten Erwärmung bei Tag durch Insolation und Luftleitung nimmt die CO_2-Erzeugung der S-exponierten Zone /II/5/ alle frühere räumliche Werte bedeutend übertroffen zu, was in diesem Falle mit der Übereinstimmung des sich im Laufe des Tages entwickelten optimalen Wärme- und Feuchtigkeitsmengen zusammenhängt. Es fällt aber auf, dass der Maximalwert im Vergleich zum üblichen Zeitpunkt der für die II/5 Kurve der vorangegangenen Tage kennzeichnenden oberen Kulminationen mit mehrstündiger Verspätung einstellt, was mit aller Gewissheit mit dem Wärmeentzug durch die am Vormittag stärkere Verdunstung im Zusammenhang steht.

Es ist zu bemerken, dass wir die tendenzwidrigen Verlauf der Kurve zwischen 10 und 11 Uhr nicht erklären können, doch ist es nicht ausgeschlossen, dass darin die Wirkung einer von uns nicht beobachteten kleineren Luftbewegung zum Erscheinen kommt.

4. Die Minderung bei Tag der CO_2-Konzentration der 20 cm Bodenhorizonte kann besonders in den Tageszeiten, da sie mit der gleichzeitigen Erhöhung der Kohlendioxidkonzentration der bodennahen Schicht zusammenfällt, schwierig erklärt

werden. Die Möglichkeit ist aber nicht auszuschliessen, dass hier die Absorption der inzwischen tiefer nach unten versickerten Bodenfeuchtigkeit eine Rolle spielt.

5. Die nach 19 Uhr ansteigenden Werte des II/20 bezeichneten Diagramms bringen wahrscheinlich bereits die Einwirkungen des hohen CO_2-Gasgehalts der 5 cm-Schicht zum Ausdruck.

6. Die erheblichen Grössenordnungen beim Anstieg der Nachmittagskurven II/5 und I/5 beweisen, dass die Kohlendioxiderzeugung der sich intensiver erwärmenden Südhangböden unter gleichmässig günstigen Bedingungen der Bodenfeuchtigkeit die mehrfache sein kann, als die der N-exponierten Hangböden. /Vgl. diesen letzteren Satz mit der Ansprache 3 des Bewertungsteils der Abb. 8/.

7. Unter günstigen Bedingungen der Bodenfeuchtigkeit kann die CO_2-Konzentration der obersten Bodenhorizonte - vor allem in der S-Exposition - höhere Werte erreichen, als in den tiefer gelegenen Zonen derselben Stellen. /Dieser Satz ist mit der Ansprache 4 des Bewertungsteils der Abbildung 8 zu vergleichen./

Von den an Karstoberflächen in Ungarn in einer waldlosen Doline der Létrástető im Bükkgebirge untergenommenen, mehrtägigen Angabenreihen heben wir unsere am 17. ung 18. August 1968 durchgeführten Beobachtungen hervor, die auch die Kennwerte des CO_2-Haushaltes der Bodengase der O- und W-exponierten Hänge neben den N- und S-Expositionen vergleichbar machen und zwar bezogen auf einen mässig windigen, doch sonnigen, warmen und einen darauf folgenden regnerischen, kühleren Tag /Abb. 11./.

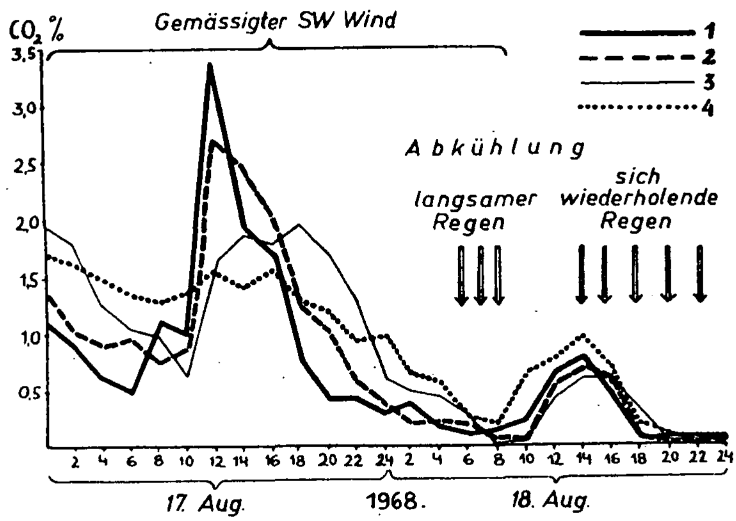

Abb. 11. Beispiel für die Bedutung der die Verkarstungsintensität beeinflussende Exposition. Veränderungen des CO_2-Gehaltes der Bodengase in den Rhizosphären von Festucae, die an den annähernd gleich steilen, aber unterschiedlich exponierten Flanken einer waldlosen Dolien /Létrástető/ des Bükkgebirges an einem warm-sonnigen und an einem darauf folgenden regnerischkühlen Tage. Die Diagramme zum Vergleich der Untersuchungsergebnisse der vom Wurzelballen entnommenen Gasproben wurden auf Grund der Beobachtungsintervallen von 2 Stunden am 17. und 18. August 1968 angefertigt /original/.

1 = O-Exposition, Festuca sulcata,
2 = S-Exposition, Festuca sulcata,
3 = W-Exposition, Festuca sulcata,
4 = N-Exposition, Festuca ovina.

Damit die aus den Expositionen folgenden Tendenzen der Bodengase durch je weniger Störungsfaktoren beeinflusst werden können, haben wir unsere Stationen auf Hangpartien mit gleichem Neigungswinkeln angesetzt, und die Wurzelzonen der Steppengräser /Festuca sulcata/ von gelichen Entwicklungsstand und gleicher Art untersucht. Da wir in der N-Exposition keine gut entwickelte <u>Festuca sulcata</u> gefunden haben, haben wir uns in die Rhizosphäre einer <u>Festuca ovina</u> mit etwas kleineren Wurzeln gelagert. Die Bodengasproben haben wir an jeder Stelle aus der 5 cm tiefen Schicht entnommen. Es ist noch zu bemerken, dass wir bei der Wahl der Doline auch darauf geachtet haben, unsere Stationen an Stellen annähernd gleicher Bodenmächtigkeit und Bodenbeschaffenheit anzusetzen.

Aus der zweitägigen Untersuchungsreibe ergeben sich folgende Schlüsse:

1. Am 17. August störte der SW-Wind /nach den Messungen von WAGNER auf dem Kurtabérc mit dem Stärkegrad 4/ den Tagesgang des CO_2-Gehaltes im Boden auf dem O-exponierten, also wesentlich windschattigen Hang am wenigsten. Hier haben wir um 12 Uhr einen Kohlendioxidgehalt von 3,35 % /also obere Kulmination/ gemessen, was zur Zeit der Luftbewegung für einen sehr hohen Wert betrachtet wird und ausser dem Strahlungsoptimum vom Vormittag auch mit dem günstigen Bodenfeuchtezustand zusammenhängt. Am Südhang, vielmehr noch in der W-Exposition kulminierte die Konzentrationskurve des Gases niedriger, obwohl am ganzen Tag günstige Strahlungseinwirkungen zur Geltung kommen konnten.Die den Höchstwert dämpfende Wirkung der dynamischen Bodendurchlüftung trat am westlichen Hang am stärksten auf.

2. Zwischen den oberen Kulminationen der Kurven der O- und W-exponierten Böden ist am ersten Untersuchungstag eine Verschiebung von etwa 6 Stunden zu ersehen. Eine Verschiebung von solchem Ausmass tritt nur unter Einwirkung der Erwärmung durch direkte Strahlung auf. Am folgenden völlig bewölkten Tag stimmen die oberen Kulminationspunkte der verschiedenen Hänge fast überein.

3. In der direkte Strahlung kaum erhaltenden N-Exposition hat die Windauswehung den die CO_2-Erzeugung bewirkenden Einfluss der Tageserwärmung durch Luftleitung fast völlig unterdrückt, und so gibt diese Kurve mit fast gleichmässigem Absteigen die für den windigen Tag bezeichnende Tendenz der Gasgehaltabnahme wieder.

/Der Umstand, dass die Untersuchung in der Nacht vom 16. auf 17. August in jeder Exposition eine verhältnismässig grosse CO_2-Konzentration angibt, hängt mit dem günstigen Strahlungs- und Bodenfeuchtigkeitswerten vom 16. August, sowie mit der Windstille dieses Tages zusammen, die an diesem Tage annehmbar in jeder Exposition zur Gestaltung sehr hoher Werte der oberen Kulmination führten. Leider können wir diese Annahme wegen Mangel an konkreten Messungen nicht bestätigen./

Obwohl es hinsichtlich des Anteils sämtlicher Wirkungskomponenten analytisch noch nicht hinreichend geklärt ist, das kann doch bereits zweifellos festgestellt werden, dass <u>die CO_2-Gasgehaltsunterschiede, die die komplexe Resultante ausserordentlich vieler Wirkungskräfte ausdrücken, expositions-orientiert sind</u>. Die Besonderheiten der Menge und des Tagesganges der Gaserzeugung, deren Vorhandensein in bezug auf die Böden der O- und W-Expositionen auch durch unsere Messergebnisse bereits ermittelt wurden, können nicht selten sogar von solcher Grössenordnung sein, wie die Differenzen gleichen Charakters der S- und N-Expositionen.

ANDÓ /1959/ fand auf den Dämmen der Theiss an einem völlig klaren, windstillen Tag die W-Expositionen im allgemeinen wärmer, und das erklärte er durch den Wärmeentzug infolge Verdunstung der am Morgen bestrahlten Hänge. Die Analogie zu suchen ist unbedingt begründet, das ist aber nach unserer Meinung nur einer der objektiv wirkenden anderen Faktoren. Für den CO_2-Gasgehalt der Dolinenhänge haben wir bisher noch keine derartigen allgemeingültigen Feststellungen getan, denn wir meinen, dass wir noch immer nicht über eine hinreichende Anzahl und auch statistische Auswertungen ermöglichende Datenreihe von den Tagen mit unterschiedlichen Strahlungen, Windverhältnissen und Niederschlagskennwerten verfügen. Unsere bisherigen Angaben unterstützen sonst auch keinen Standpunkt kategorisch, denn im Laufe unserer hier nicht detaillierten Messungen gab es Fälle, wobei die westlichen, aber auch solche wobei die östlichen Expositionen den höheren Betrag der täglichen CO_2-Erzeugung aufwiesen. /Vergleiche diese Frage noch mit den detaillierten Untersuchungsergebnissen der Wärmegangs und der Bodenfeuchtigkeit der Dolinenexpositionen./

Nachdem die CO_2-Erzeugung im Boden und sein globaler Kohlendioxidgehalt ein entscheidender Faktor für das Agressivwerden sie durchsickernde Niederschlagswässer, und so dadurch auch der wichtigste Determinant des lokalen Ausmasses der Verkarstungsdynamik ist, kann für fast sicher genommen werden, dass z. b. die Ungleichförmigkeit der Dolinen nicht mit den von CHOLNOKY und seinen Anhängern angenommenen lithologischen, stratigraphischen /streichens- und fallens-orientierten/ Ursachen, sondern mit den hier dargestellten mikroräumlichen Faktoren in kausaler Verbindung ersten Ranges steht. Nur so kann es vorkommen, dass die in räumlich unterschiedlich angeordneten Kalksteinschichten entstandenen Dolinen in bezug auf ganze Gebirge übereinstimmende Richtungen der Deformationsachse haben, wie das durch unsere im Bükkgebirge, im Nord-Borsoder Karst, im Mecsek und auf mehreren Karstplainen Kroatiens in diesem Sinne durchgeführten Messungen bewiesen wurde.

Sonst haben die verschiedenen Pflanzenindividuen und Assoziationstypen unbedingt ihre artenspezifischen Begebenheiten für das Antreiben der CO_2-Erzeugung im Boden bzw. die Bestimmung des Ausmasses der Bodendurchlüftung, sogar in bezug auf karstige Pflanzengesellschaften. Auffallend wird das beim Vergleich der Bodengase der Wälder mit den Bodengasen der Steppenwiesen, denn im Boden der Wälder ist die CO_2-Gasmenge immer beträchtlicher, als die des Bodens der Wiesen ohne hölzernen Gewächse. Dieser Unterschied geht sogar auf mehrere Ursachen zurück. Von ihnen halten wir für die wichtigsten die folgenden:

1. Der Feuchtigkeitsgrad des Waldbodens ist wesentlich günstiger und zeigt kleinere Extremitäten, als der Boden der Steppenwiesen.

2. Der Waldboden ist durch die Laubkrone vom Wind geschützt.

3. Der Waldboden ist zumeist von einer horizontal geschichteten, zusammenhängenden Schicht von Laubresten bedeckt deren die Durchlüftung hemmende Wirkung beträchtlich sein kann.

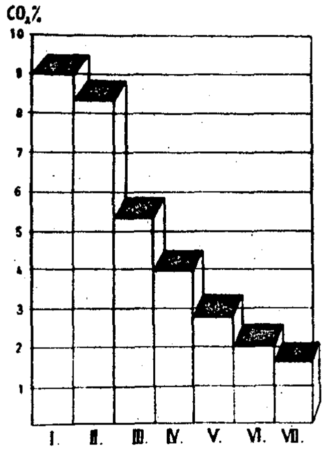

Abb. 12. Vergleichsdiagramm der aus den Rhizosphären verschiedener Pflanzenarten karstiger Steppenassoziationen, sowie aus den 5 und 10 cm tiefen Zonen des Bodens unterschiedlicher Waldtypen gewonnenen Maximalwerte der CO_2-Konzentrationen im Frühjahr. Die Messungen haben wir im Bükkgebirge, bzw. in Nord-Borsoder Karst in den Monaten April und Mai der Jahre 1967 und 1968 an klaren, windstillen Tagen durchgeführt /original/.

Entnahmestellen der Bodenluftproben:

I = in einem Eichenwald, unter einem mehrere cm mächtigen, zweijährigen, feucht konsistenden Laubrestfaden,

II = in einem Buchenwald, unter einem mehrere cm mächtigen, zweijährigen, feucht konsistenden Laubrestfaden,

III = in einem Fichtenwald, unter dem Teppich sich zersetzender Nadelreste, etwa in 8 cm Tiefe,

IV = aus der Wurzelsphäre der Nardus stricta, vom sauren und tiefgründigen Boden einer Doline auf dem Bükk-Plateau,

V = aus der Wurzelsphäre der Festuca sulcata in der Steppenwiese einer SO-exponierten Dolinenhänges mit Felsenflecken bei Aggtelek,

VI = aus der Wurzelsphäre der Festuca ovina in der Steppenwiese eines N-exponierten Dolinenhäng mit Felsenflecken bei Aggtelek,

VII = unterhalb einer Carex humilis, in 5 cm Bodentiefe, in der Steppenwiese einer SO-exponierten Dolinenhanges bei Aggtelek.

4. Diensausgedehnte und tiefreichende Rhizosphäre des hölzernen Gewächses erhöht bedeutend die Tiefe der vom Gesichtspunkt der subcutanen CO_2-Erzeugung aus wichtigste biologisch aktiven Bodenzone und dadurch die der Einheitsfläche angehörende Anzahl des Edaphons.

In Abb. 12 stellen wir einige kennzeichnende Danten von unseren Beobachtungen dar, an Hand derer wir die oben angeführten Ansprachen abfassen konnten. Es scheint so, dass die vom Gesichtspunkt des Karstprozesses aus günstigsten Bodengasverhältnisse in den ungarischen Karstgebieten unter den Eichen- und Buchen-Assoziationen entstehen und bereits die Gaserzeugung der Karstbuschwälder, insbesondere aber die der Steppenwiesenböden hinter jenen dieser Wälder zurückbleibt. Aber sogar in den Fichtenwäldern ist der Kohlendioxidgehalt des Bodens höher, als in der Steppenvegetation!

In der Rhizosphäre der Grasvegetation haber wir die CO_2-Höchstwerte merkwürdigerweise bei der die Feuchtigkeit und Kühlheit liebenden Nardus stricta am höchsten gefunden, was wir nur als spezifische Eigenschaften erklären können, denn die Wurzelzonen der in der Forschungszeit hinsichtlich der Erwärmung in wesentlich günstigeren Expositionen untersuchten Festucae und Carices hatten auch optimale Bodenfeuchtebedingungen.

Hier erwähnen wir, dass die wertvellen Untersuchungsergebnisse, worüber BALÁZS /1964/ berichtet, in bezug auf die beständigen Zusammenhänge zwischen der Zusammensetzung der Karstquellen der gemässigten Zone und den zu ihnen gehörigen Vegetationsverhältnissen der karstigen Einzugsflächen, bestätigen gleichfalls die grössere Kohlendioxidmenge in den

Boden Waldvegetationen, wodurch sie die kennzeichnende Durchsetzung der auf die Verkarstungsdynamik ausgeübten Wirkung des Vegetationscharakters betonen /Abb. 13/.

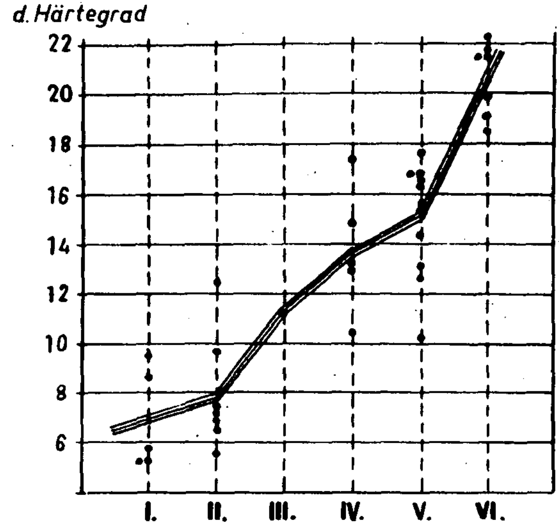

Abb. 13. Zusammenhang der Kalkhärte der Karstquellen unter der gemässigten Zone mit der Vegetationsbedekkung, bzw. Vegetationstypen der ihnen angehörigen Karstoberflächen des Einszugsgebietes. Die römischen Ziffern bezeichnen die unten stehenden Gruppen /Angaben von BALÁZS/:

Gruppe	Oberflächenverteilung des Einzugsgebietes			Durchschnittliche Härte der untersuchten Wasserproben
	Wald	Wiese, Weide Buschwald	Felsige Kahlfläche	
I.	-	0-10	80-100	7,0 nk°
II.	-	30-60	40-70	7,8 nk°
III.	max. 10	60-90	10-40	11, 2 nk°
IV.	0-25	75-100	max. 10	13,7 nk°
V.	25-75	25-75	max. 10	13,0 nk°
VI.	75-100	0-25	max. 10	20,7 nk°

Bei der Beurteilung der Frage durften wir natürlich auch die Bodenlebewesen nicht ausser acht lassen, da die Bodentiere ja auch durch das Ausscheiden ihrer Stoffwechselprodukte zum Umwandlung der Verbindungen von Bodengasen unbedingt beitragen. Für die Bestimmung der Grössenordnung dieser Wirkungsseite und ihrer Durchsetzung in der Karstkorrosion sind aber bisher keine Untersuchungen vorgenommen worden.

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J. K u n a v e r

THE HIGH MOUNTAINOUS KARST OF JULIAN ALPS IN THE SYSTEM OF ALPINE KARSTS

A number of papers have already dealt with different alpine or high mountainous karsts of the Alps or other European mountains, but at the same time one misses comparative studies. There exist, of course, comparisons of surface landforms, of their morphology and sometimes also of their dimensions. But we miss still more that sort of comparisons which could answer general morphogenetic problems of alpine karsts and problems of their similarity and diversity, or with other words, the questions of the origin and types of the high mountainous karst physiognomy.

In order to be able to do this kind of work there is first to be done an important task of establishing the elementary types of high mountainous karst physiognomy. It is understandable, that owing to many reasons such works have not been done in most of these alpine areas. I think that especially the technical problems and the diversity of geomorphological mapping of a such a morphologicaly rich relief make comparisons even more difficult. But we can try to overcome this either with unification of geomorphological mapping or with acceptance of a classification of types of alpine karst, some of which are going to be proposed in this paper. The detailed mapping of this surface demands the use of a very big scale for many of the karst objects are small. For the general physiognomy they are not really important, but they express the nature of actual karst processes.

To avoid an extremely long-lasting and therefore technicaly hardly practicable detailed mapping we propose the use it only in cases of representation of elementary types. Such types of alpine karst relief are in fact specific geomorphological complexes or associations of forms which could be represented with one sign only.

In this paper the author would like to represent the attempts for geomorphological mapping of high mountainous karst with help of detailed mapping as well as with help of system of types of high mountainous karst. The mapping has been done in a massif of Kanin which is a part of the western Julian Alps. There will be shown also the most important qualities of the karst of the Julian Alps itself.

I.

The phenomenon of karst in the Julian Alps is being known for nearly one hundred years. The geologist C. Diener /1884/ compared the barren karren pavements on the Komna with those of the Steinernes Meer and the Totes Gebirge and he did not find any special distinctions in its great expressiveness. Later on it has been established that in general this estimation can be sufficient because there are many similarities between the karst areas on the northern and the southern border of the eastern Alps, as far as the surface is concerned. Of course, a detailed comparison, which would be of great importance, should still be done. We expect from this research that it can answer many questions which are connected either with somewhat different general geomorphological development or with slightly diferent nature of climate in both regions.

The karst areas in the Julian and also in the Kamnik Alps, have been sistematically explored in the last twenty years, as well their speleological and the surface karst phenomena /Kunaver 1961, 1969/. The Julian Alps are very rich in vertical chasms of which some 300 or more have already been explored. One of the longest Yugoslav caves and the deepest has also been found in the Julian Alps near Tolmin. A great number of speleological objects is not in accordance with comparatively moderate dimensions, but as the results of the latest thorough exploration show bigger numbers could be expected. The specific character of our alpine karst has its origin in the first place in a very thick limestone and partly also in dolomite strata of Noric and Rhetic age. The Dachstein limestone and Haupt /Main/ dolomite attain in the Triglav north wall the thickness of up to 1500 meters. However, there is a lack of impermeable layers throughout the heights ob the Julian Alps. The water outlet from the surface is therefore, with exception of some small patches to the southwest and to the south of the Triglav, nearly every-where extremely dispersed. We are convinced that this dispersion has been progressing from the beginning of holocene because of the progress in karst dissection, at least on the surface. The other reason for the lack of surface waterflows is the deep incision of the alpine massifs with the valleys. The underground waters are situated mostly deep in the calcareous interior. The risings are as a rule near the local erosional bass at the foot of slopes.

Some other data about the conditions for surface karst phenomena in the Julian Alps:

- The remains of the younger terciary relief are of similar nature as the ones on the northern border of the eastern Alps. They have a step-like nature descending from the highest platforms round the Triglav /in the heights of 2400 - 2500/ mostly towards south, south east and south west. To the west of the Triglav there are only Križki podi and Kaninski podi, two excellent examples of our alpine karst. Podi is the local Slovene name for the karstified plateau above the forest limit. The Kaninski podi or karst plateaus of the massif of the Kanin is the second largest area of alpine karst. It is famous because of a very intensive karst processes and expressive karst forms. The karst area of the Triglav massif covers about.

- The climatic particularities of the Julian Alps are the extremes in precipitations, at least in the western part. The Kredarica /2515 m/ gets on the average 2080 mm/in the period 1954-1962; the average amount is too low because of exposure to strong wind/, the Kanin gets on average 3418 mm /1953-1964/, the mountains to the west of the Bohinj lake do not get much less either.

- The actual forest limit on the southwestern side is not higher than 1500 m; however, in the central part it rises up to 1900 m.

- According to the results of a chemical analysis of karstified limestones, in the massif of the Kanin there are often transitions in apparent pure Dachstein limestones to dolomitic limestone of different composition. A small percentage of dolomitic addition could already be of decisive importance for the existence, dimensions and the physiognomy of the macro as well as for the microkarst forms in subnival conditions. The influence of the slight dolomitisation is being displayed in strong mechanical desintegration of the rock in lower heights. Next phenomenon is the disappearance of the smallest forms corrosion of.

- The strata of Dachstein limestone, which mostly carry the typical karst forms, are thick bedded, from 0,5 to 1,5 m. They are widespread. The limestones and dolomitic limestones of the Ladin age, to the south of the Triglav, are also karstified. But they dont have such diversified karst relief as it is normal for the Dachstein limestone. Above them there are the Triglav limestones, which are dolomitized and not stratified. They are therefore only slightly karstified. The youngest calcareous rock is the upper jurassic limestone which appears in alongated patch in the valley of the seven Triglav lakes and it is strongly karstified.

- In the areas of our alpine karsts the strata are rarely tilted for more then 30^{o}, but also the horizontal strata are not very frequent.

- There is a great dependence of bigger karst forms from the system of joints, master joints and also from faults. We have soon established an especially close relation between master joints and the kotliči or dolinas with vertical walls, which are therefore often of elongated or rectangular shape. Of course, the karstsgassen kluftkarren, elongated dolinas and other karst forms are even in a more direct relation to the joints and faults. In the massif of the Kanin there are up to four systems of differently orientates joints and faults and of different frequency. A great density of them contributes a lot to the high karstic dissection of that area.

- The traces of glaciation are very frequent in the highest parts of the Alps and they have the same importance for the morphogenesis and phisiognomy of the karst surface as it has been established in other alpine karsts. The pre-würmien age of bigger karst depressions, and also of some kotliči - dolinas with vertical walls, has been established too /Haserodt, 1965/.

Most instructive is the way of a progressive withdrawal of glacial drift /mostly of calcareous and partly of dolomitic composition/ on the one side and the succeeding of karst forms on its place. In placess where older depression or faultlines existed below glacial till, big dolinas and karstgassen have arisen there. In other places the retreat of glacial drift is in direct relation to the surface corrosion and denudation. We find glacial striae untouched even beneath 10 cm of drift. That is in agreement wirth the statement of Williams /1966/ who has noticed different relations beetween glacial drift of various composition and the underlaying calcareous rock.

II.

As far as the data about the karst surface forms are available from the Northern limestone Alps, we can say, that they are more or less phisiognomicaly indentical with those in the Julian Alps. It is more difficult to say anything about the dimension except with regard to the bigger depressions and dolinas which are well described. There is still a lack of statistical information which could more easily enable us to make any kind of qualitative and quantitative comparisons.

On the bases of the work of Haserodt /1965/ in the Hagen Gebirge and surroundings we are able to englighten some of the specific characters of the alpine karst in the Julian Alps:

1. The Nischenkarren are abundant in our conditions. But the Kamenitzas are more frequent. Haserodt does not mention them at all. Kamentizas, as for the rule, can develop practically on every suitable barren rock surface below the zone of stronger mechanical desintegration, expect in the forests on in the vicinity of denser vegetation.

2. The Firstkarren could be found in similar places. But they are much more frequent then Kamenitzas. They could exceptionally also be found on lonely standing stones or on barren rock surface below forest limit.

3. Karrentische are more rarely to be found, as well as Karrendorne.

Other smaller surface forms have similar appearence as ones on the northern alpine border.

4. In our conditions the dolinas in glacial drift, as well as secondary dolinas in bigger depressions are quite common and also the elongated dolinas in dry valleys. Bigger dolinas with over 15 m of diameter are to be found except in drift also in more dolomitized bedrock in all heights. In the middle of zone of more intensive mechanical desintegration, which begins in the western Julian Alps in height of round 2100 m, there are in compact limestone rock most frequent the transitional forms between kotlič and funnel-like dolina, whereas in more dolomitized bedrock prevail only the latter.

5. As we have already mentioned one of the most frequent appearance above the forest limit are the dolinas with vertical walls, of angular or rounded plan, which are called kotliči or kettlelike dolinas. The relation between diameter and the dep is most often 1:1. Normaly the dimensions do not exced 10 m. But we have not been able to make clear yet, wheather these are the same as Steilwanddolinen or Kesseldolinen /Haserodt, 1965; Zwittkovits, 1963/. One is nevertheless certain, that kotliči are a usual phenomena on thick bedded and strongly jointed limestone and they are the result of nearly equal effect of chemical and mechanical desintegration of the rock. This means that the kotliči are a specific sort of subnival dolinas. Besides, the fosil kotlici-like forms have been found in the Trnovski gozd in the heights between 800 m and 1200 m as a remains from colder pleistocene climate /Habič, 1968/.

6. There exists rather great similarity also in the shape and dimensions of bigger depresions, as well in morphogenesis, and age. A local name konta is used for all depressions in the Alps which are uvala-like. According to dimensions there could be Gruben or uvalas with many transitions, but they do not exceed 500 m in diameter and are usually shallow. The Velo an Malo polje below the Triglav are an exception as being a sort of high mountainous karst polje /Gams, 1963/.

7. In connection with the discussion about the vertical zonation and the prevailance of some typical karst forms we must stress that the local conditions are very often not in agreement with general schemes, which have so far been constructed. We agree with Haserodt's critical views that only the products of post pleistocene karst denudation could be of decisive importance for climatic conditioned vertical zones with prevailance of specific processes and typical micromorphological complexes.

But the situation in the Julian Alps and very probably also to the north of it seems to permit a division of alpine karst not only in two main vertical zones as Haserodt suggested. These are silvinen-bewaldeten karst and barren nor forested or subnivaler alpine karst. We propose to devide it in four main height zones which are the result of the fluctuations of climate and the vegetational zones in holocene and very much influenced by the man's activity. By determining vertical zones we can state, that a zone between the forest limit and the zone of a stronger mechanical desintegration, which is in the Julian Alps from about 1900 m to about 2200 m, was never in holocene for a longer period of time under the influence of totaly different conditions as they are to day. This is therefore the main zone of typical barren high alpine karst. Considering this fact we can divide the silviner and barren zone of alpine karst in the following four vertical zones:

1. the zone of proper silviner or wooded karst below the forest limit: less or more frequent dolinas, esspecially bigger ones, konte - uvalas and dry valleys.

2. the lower transitional zone of alpine karst around the forest limit: all sorts of rounded karren, beginning of appearance of kotliči and other subaerial corrosion forms.

3. the zone of barren alpine karst with complete inventary of karst forms typical of those conditions: besides of all sorts of karren and microcorrosion forms, which are most common on different kinds of pavements, most typical are kettle-like dolinas or kotliči; the remains of dry valleys., different kinds of dolinas and bigger depressions.

4. the upper transitional zone of barren alpine karst which is identical with the lower zone of stronger mechanical desintegration: the transitional forms of kotliči to normal dolinas in the scree and in the bedrock; an expressive retreat of microcorrosive forms.

III.

In spite of the fact that bigger surface karst forms are not suitable as the typical height zonal indicators /with the exception of kettle-like dolinas, kotliči/, they could be of much bigger use when we wish to show physiognomic and often also geneticaly specific types of alpine karst not regarding the height or climate zones. We have been trying to find the so-called elementary morphological types of alpine karst which are by no means only the results of climate but at the same time the expression of complex mutual effects of many statical and dynamic agents. In addition to the climate, the group of other geological factors is of the greatest importance, among them especially the petrographic and chemical nature of the limestone, then the thickness of strata, the relation between the dip of strata and the inclination of surface and lastly the jointing of the rock. Of course, the formation of the relief in pleistocene with the erosional and accumulation traces have also caused, that the karst surface has not everywhere equally started the further geomorphological development in holocene.

In this light it is possible to recognize different types of alpine karst as a morphological complexess, which could be of elementary kind or of higher type composed with help of elementary ones. The purpose of this kind of morphological classification and typification is first of all to make the geomorphological mapping easier than it is mapping of every karst form separately. The latter is difficult to do in greater extent especially in case of microcorrosion forms. However, in elementary morphological complexes also the smalles karst forms could be considered. This method also enables an objective comparison between different karst areas. Such comparison could reveal and make understandable many hidden reasons and problems, which seem to be unexplainable at first sight, particulary in case of lack of climatological and geological information.

As an excellent and necessary resource in determination of subtypes and types a micromorphological mapping of smaller areas has been proved. It only gives a total insight into the inventory of karst forms as well as in the morphogenetic relations between them. Because of the chosen scale /1:500/, it is possible to make only a representative examples.

We have mapped two similar pavements which have a little different inclination of the surface /10° and 19°/. Both pavements are situated in the southwestern mountains of the Kanin in the height of 1900 m.

Without detailed analysing of the micromorphological differences between both pavements they are fine examples of typical alpine glacio-karstic surfaces and as such both examples of elementary morphological types. According to the system which we propose in continuation we could call the pavement A a flat pavement, and the one of B a subconformed type of stepped inclined pavement. Both of them have such inventory of karst forms, which is in accordance to many given conditions, in first place of course in accordance to the height. The unchanged statical elements as for instance the geological are and also the same type of pavement can be in other climatic respectively height conditions the basis of a somewhat changed inventory of forms. Thus the subtypes of surface morphological complexess could be separated.

The groups of elementary morphological complexess or types are at first divided with regard to the litological nature of the surface. The principle of further differentiation follows the distinction between the levelled and the inclined karst relief. Lastly the basic distinction is considering the elementary types and perhaps further also the subtypes.

As we see, the basic starting point are the relations between structure and a slope or general surface morphology, especially in case of karst surface in solid bedrock. Also the Bögli's Schichtreppenkarst /1964/ is an example of elementary type or subtype. We have been using also some of the William's /1966/ definitions and examples of different kinds of pavements. They are similar to alpine ones because of the similar origin, not regarding their rather low location in different places of British Isles.

Thus the system of glaciokarstic or alpine karst morphological complexess - types looks as follows:

I. The karst in solid limestone bedrock.

A. The types of karst on the leveled relief.

a. the flat pavements /Schichtreppenkarst after Bögli/, dip from $\approx 0^\circ$ to 10°.
b. the inclined pavements with cuestas /dip $< 45^\circ$/.
c. the levelled surface without pavements /dip $> 45^\circ$/.

B. the types of karst on slopes $< 45^\circ$

a. the stepped flat pavements /dip from $0^\circ - 10^\circ$/
b. the conformed inclined pavements /dip slope, dip $10^\circ - 30^\circ$ /45°/.
c. the subconformed type of inclined pavements with scars /dip > slope/.
d. the subconformed type of stepped inclined pavements /dip < slope/.

e. the transverse type of inclined pavements /the direction of dip is for about 90^{o} different from the direction of the slope.

f. the reverse type of inclined pavements /the direction of dip is about 180^{o} different from the direction of the slope.

g. very steep or vertical slopes smoothed by glacial erosion and often dismembered by paralel Rinnenkarren.

C. the transitional type of karstified slopes with alternation of conformed inclined pavements, benches and steep scars.

D. a. the karstified relief of rochees mountonees with passages to surfaces covered with glacial drift.

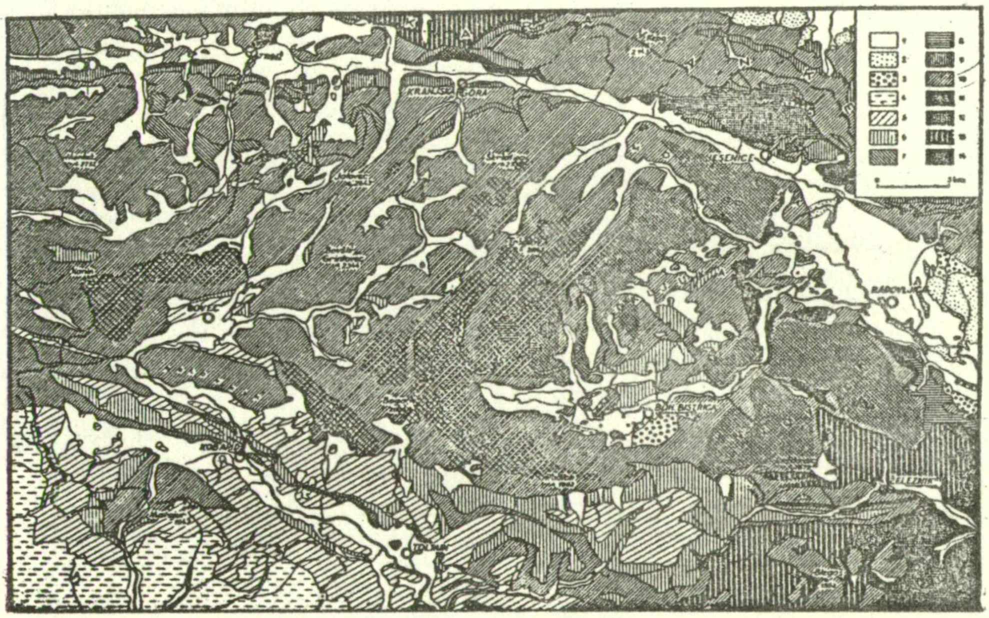
II. The alpine karst on less compact, thinly bedded, less pure or dolomitized rock, in glacial drift of carbonate composition and in rubble.

A. a. the dolinas in extremely jointed bedrock.
   b. the dolinas in dolomitized limestone.

B. a. the dolinas in glacial till and in rubble.
   b. the elongated dolinas and elongated dolinas like trenches in Karstgassen.

C. a. less typical karst surface, covered with rubble as the result of mechanical desintegration or because of dolomitisation.
   b. slopes, covered with glacial drift, karstified on benches.
   c. slopes in dolomite and dolomitized limestone.

Bigger karst forms as bigger dolinas, all sort of uvalas, karstgassen, dry valleys etc. could however be marked on the geomorphological map separately. There is of course in the proposed system also enough place to enclose other elementary types of karst surface, which are characteristic for other alpine karsts.



Geological Survey and the Hypsometric Types of Karst of the Julian Alps

the subalpine karst areas below forest line;

the transitional zone of alpine karst around forest line, 15oo-18oo m;

the alpine karst areas above forest line, up to 25oo m .

1.Quaternary;2.Miocene;3.Oligocene;4. Eocene;5.Cretaceous;6.Jurasic;7.Rabel strata;8.Wengen strata;9. Werfen strata;1o. Triassic,prevailing limestone and dolomite;11. Permian;12.Carboniferous;13.Old Paleozoic;14.Porphyry.

R E F E R E N C E S

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S. Láng

QUELQUES QUESTIONS DE LA DÉNUDATION DES KARSTS ET DE LEUR ENTOURAGE EN HONGRIE

La détermination de la vitesse d'enlevèment récent, de l'épaisseur des couches dénudées du karst ancien des calcaires et de la jeune masse montagneuse de couverture dénudée meuble se faisait attendre jusqu'ici encore et aucun résultat concret n'est pas encore connu. En fait, l'épaisseur totale du jeune paquet de couches non karstique dénudé de l'époque tertiaire peut être plusieurs fois autant que celle des roches calcaires et dolomitiques anciennes et dures mésozoiques du Tertiaire inférieur. Il est surtout difficile d'établir le degré de l'enlèvement dans le cas, où il y a plusieurs centaines de mètres de différence d'altitude entre la plateau karstique et l'avant-pays non karstique d'au-delà de la jeune faille marginale.

On peut déterminer l'enlevèment de la zone de contact karstique et non karstique - pour les dernières deux à trois millions d'années - le mieux rapprochant dans les karsts qui se sont soulevés relativement peu au-dessus de leur entourage non karstique et qui ont relié à leur réseau hydrographique - dans la partie des pertes de ruisseau - par l'intermédiaire de la bathycapture définie par L. JAKUCS /1962/ - même une surface karstique d'une étendue considérable. Un terrain de cette espece est la surface karstique entre Aggtelek et Jósvafő comportant le réseau de cavernes de Baradla.

La circulation de matériel du vaste réseau de cavernes est assurée par un bassin de réception d une surface de 30 km², d'où les eaux s'écoulent par les ponors dans la caverne. Les données caractéristiques de la circulation de matériel de la caverne de Baradla sont - calculées pour la dernièr million d'années - les suivantes:

a/ La moyenne annuelle des précipitations atteint 600 mm, soit 600 000 m³/an,

b/ L'écoulement du bassin-versant total est de 100 mm/an, soit 100 000 m³/an,

c/ L'épaisseur moyenne des sables et cailloutis enlevés de la surface non karstique est de 10 à 12 m.

d/ Le degré de dissolutin dans le karst en amont du Baradla est environ de 100 m³/an.

Le total de la circulation du matériel se constitue à la base des précédents comme suit:

a/ Les précipitations /provenant d'une surface de 30 km²/font dans un million d'années 18.10^{12} m³.

b/ L'écoulement à travers la caverne /provenant d'une surface de 30 km²/ fait pendant un million d'années 3.10^{12} m³.

c/ Le degré de dissolution et d'érosion apres les précipitations pendant un million d'années font /d'après les données de D. BALÁZS/ 100.10^{6} m³.

d/ En résultat de 1 effet dissolvant /lo g /l / des eaux écoulées à travers la caverne les matériaux évacués pendant un million d'années font 30.10^{6} t - 12.10^{6} m³.

e/ Les matériaux sableux et caillouteux sortant par la caverne où y arrivant /calculés pour un million d'années/ font 300.10^{6} m³.

f/ La compacité des alluvions transportées par les eaux s'écoulant atteint selon les précédents 250 mg/m³.

Pour vérifier ce qui a été dit, nous avons recours a la succession des vallées larges et profondes menant aux ponors d Aggtelek et à la série de plaines plates, larges de quelques centaines de mètres situées le long des ponors, et dont la couverture de cailloutis sableux a été déjà enlevée et charriee à travers la caverne. Le degré de l'érosion non karstique peut être estimé réduit: dans l'alignement des bathycaptures il y a des parois rocheuses abruptes ne s'élevant qu'à une hauteur de 20 à 60 m et qui se sont modelées par éboulement et reculement. En fait, cet alignemetn de bathycaptures devait être initialement aussi recouvert d'une nappe composée de graviers et de sables du Pliocène superieur dont le dépot pouvait s'effectuer il y a 3 à 4 millions d'années d'apres les données historiques de l'évolution des vallées fluviales plus importantes de l'entourage.

En tout cas il faut aussi prendre en considération l'érosion constante du karst entier et des terrains non karstiques du voisinage. La perte annuelle du karst d'Aggtelek par la dissolution du calcaire /D. BALÁZS 1964/ atteint 1700 m^3/an 120 km^2 équivalent a une couche épaisse de 15 m/ 1 million d'années. Mais il n'en est que la partie mineure /de 6 à 7 m/ qui se fait valoir en surface karstique, tandis que l'autre partie /de 7 à 8 m/ dans l'intérieur du karst par le réseau hydrographique spatial.

L'action des mouvements de l'écorce terrestre, dans le cas des soulevements en dôme, de même que l'importance de lafaille marginalc, n'est pas remarquable, ayant au plus un rejet de quelques dizaines de mètres. Autremant des branches latérales sèches et bien remblaées, soulevées plus haut devraient se présenter éventuellement par des aovertures anciennes, n'étant plus actives, s'ouvrant à un niveau plus élevé, avec des restes de gouffres. Mais aucune cavité de telles sorte n'a été découverte jusqu'ici. Même les plus grands soulèvements du karst /Poronya-tető, Baradla-tető/ ne dépassent que de 80 à 100 m les points culminants du bassin-versant à bathycaptures. C'est avec un faible soulèvement en dôme et avec des failles de faible dimension qu'ils se sont élevés de quelques dizaines de mètres au-dessus de l'avant-pays sableux-caillouteux. Les jeunes mouvements de la croûte terrestre sont témoignés probablement par les salles du Baradla dépassant par endroits la hauteur de 50 m et les monts d'éboulis y élevant.

En effect, le caractere identique de l'évolution superficielle consiste en ce que sur la presqu'île d'Istrie des chaines calcaires mésozoiques s'alternent avec des bandes de flyches imperméables et aux contacts p. e. à la ligne de Postojna et ailleurs des successions de ponors se sont constitués a maints endroits autour des ponors avec de petites plaines de diametre de 500 m environ. Ces dernières s'encaissent en forme de bassin, mais a parois abruptes à une profondeur de 100-150 m dans le terrain de flysch vallonné. Le système de vallées présente des bathycaptures.

En comparaison des petits encaissements mentionnés profonds de 100 à 150 m - au contact du calcaire et du flysch - avec les plaines et les bassins réduits semblables à ceux de Baradla en Hongrie formés à l'alignement des bathycaptures, la ressemblence génétique se montre indispensablement entre aux, mais aussi la difference de dimension. Les petits "bassins aux ponors" aux environs de Postojna ou de Skocjan sont de 3 à 4 fois si larges et profonds que ceux aux environs de Baradla. /Il se trouve aussi d'ouvertures béantes de gouffres comme p. e. dans la cas des cavernes de Skocjan./

Le modélage des formes en liaison avec la bathycapture étant semblable à celui aux environs de Baradla, les differences considérables de dimension des formes génétiques semblables peuvent être attribuées aux différences climatiques. Contre les 600 mm de précipitations à Aggtelek, la région de Skocjan-Postojna-Rijeka située dans la zone méditerranéenne dispose d'une précipitation annuelle de 1300 à 1500 mm. Par contre, le nombre des jours pluvieux est moins grand qu'en Hongrie et l'intensité moyenne en est de 3 à 4 fois plus élevée que les valeurs en Hongrie. Il en de même avec le maximum de l'intensité de précipitation, La probabilité d une précipitation de 80 à 100 mm/24 heures est de 10 ans environ a Aggtelek contre, 0,3 ans en Istrie, ici de même la probabilité d'une précipitation de 200 à 400 mm/24 heures est de 10 à 15 ans environ, tandis queune pluie de telle mesure n'existe point dans les karsts hongoris. De telles pluies abondantes dans les karsts d'Istrie peuvent résulter seuls sur les petits bassins de réception à bathycaptures d'une superficie de 5 km² dé tres grandes quantités d'écoulement: apres une pluie de 80 à 100 mm sur une superficie de telle grandeur 200 à 300 mille m³, et apres une averse de 200 a 400 m³ 1 a 1,5 millions de m³ d'eau s écoulent dans le karst pendant quelques heures par les ponors, ce qui entraîne un mouvement turbulent et la constitution et le modélage continuel de petites dépressions karstiques autour des ponors.

Tout ce qui a été dit témoigne que dans les processus de karstification les conditions de précipitations devraient jouer, la répartition temporelle des précipitations doit jouer un rôle de premier ordre et que dans le modelage des dimensions de chaque forme karstique ou des formes complexes dues aux processus karstiques, l'intensité de précipitations élevée et avec cela le courant d'eau intense peut jouer aussi un rôle /p. e. dans la cas des dépressions aux ponors mentionnées de caracteré et d'origine érosive/, tandis que dans le modelage des formes karstiques d'autre espece c'est le ruissellement lent, tout de même constant et abondant qui est d'une importance capitale comme p. e. dans le cas de la karstification superficielle, de la corrosion superficielle ou souterraine et son inverse, la précipitation du calcaire. Mais pour l'efficacité des derniers processus à côté des précipitations continuelles et à peu près uniformes c'est la température dominante, ensuite une série d'autres facteurs qui deviennent de plus en plus importantes.

P. Müller - I. Sárváry

PURE CORROSIVE MODEL OF THE DEVELOPMENT OF VERTICAL KARST-SHAFTS

In the northern part of Hungary some outcrops of Triassic limes-stones have brought about extended karstic regions. On the plateaus of these mountains many dolinas and many vertical shafts /in Hungarian: "zsomboly"/ are to be found. In many cases the entrances of these shafts are situated on the upper part of the dolina-slope. The entrances are very narrow when compared with the depth.

It is characteristic that these shafts are frequent in small areas. For instance on the "Alsóhegy"-plateau in Northern-Hungary more than 50 shafts are known in an area of 12 km² extent, seemingly in irregular distribution.

It is difficult to explain the abundance of the cavities supposing that they are independent fossil swallow-holes. That is why we tried to explain their origin with an actually working effect /Principle of Actuality/. According to our hypothesis the vertical shafts have to come into existence on certain conditions which are recently wide-spread too.

Thus the karst-shaft is one of the general karst-phenomenas.

Items of the teory

A./ The shafts /as the dolinas/ have a corrosive origin.

B./ The shaft starts to develop on the deepest point of the dolina.

C./ The cavern of the shaft develops downwards.

D./ During the process the deepest part of the dolina changes its place.

E./ The precipitation infiltrating on the surface of the dolina is sufficient to dissolve the lacking rock-mase. It is not necessary to suppose bigger catchment area.

The items are successively discussed.

A./ The corrosive origin of the vertical shafts

According to the wide-spread opinion /Moravetz 1965/ the dolinas have their origin due to corrosive processes. This process is taking place at a shallow zone under the bottom of the sinking, along the openings and on the rock surface. This sinking acts as a trap for the snow and for the organic matters /Terzaghi 1912, Geze 1965/, consequently the precipitation infiltrating on its surface is higher than the average and this precipitation gains more carbon-dioxide than the average from the soil and leaf-litter deposit. Consequently the thickness of the corrosive zone in only about a few metres.

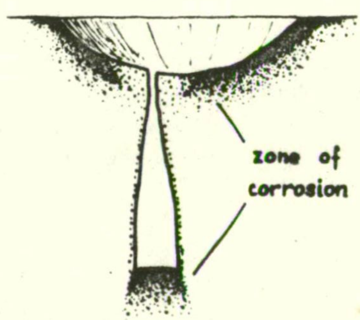


Fig. 1.

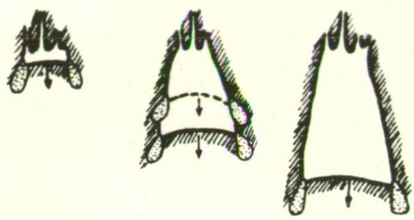
The water percolating through this zone is practically saturated with hydrocarbonates. Where the zone of corrosion is crossed by a fissure or joint, a discontinuity arises. The water runs down quickly to the bottom of the fracture. The drain-effect tends to accumulate water from the surrounding. The humus deposit at the bottom of the fissure intensifies the effect of corrosion.
Consequently the shaft is a discontinuity in the corrosion-zone of the dolina, where a part of the zone gets down to a lower level /Fig. 1./. The bottom of the shaft is sinking by corrosion.

B./ <u>The shaft starts to develop on the deepest point of the dolina</u>

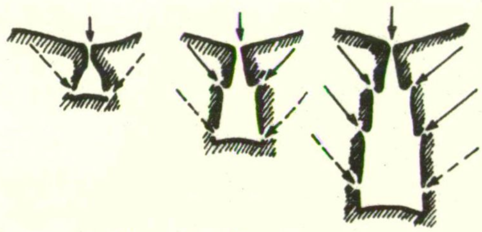
According to the potentialities, several shafts may start to sink simultaneously in the same dolina. The hole situated in the very bottom of the dolina exerts a drain-effect to the other holes, and their development thus is restrained. So the hole at the deepest pont has the biggest catchment area.

C./ <u>The cavern of the shaft develops downwards</u>

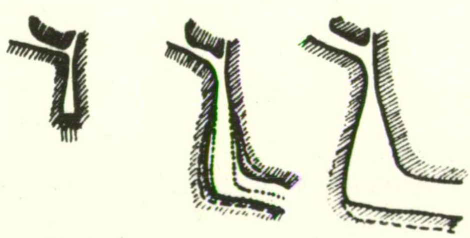
The water running down on the wall of the shaft has no time enough to become fully saturated. It can dissolve rock material mostly at places where it slows down. Therefore the corrosion is taking place chiefly near the bottom of the cavity. This part turns into the now corrosion-zone. In this zone the water becomes practically saturated and percolates down without enlarging the lythoclases. Though the water flowing down on the walls makes the cavern more spacious, the growing is chiefly the result of the deeping. The drain-effect and the erosion-effect grows with the dept, and this contributes to the shaping of the sugar-loaf-like form of the shaft /Fig. 2./.



a,) zone of corrosion is near to the walls



b.) quantity of water increases in function of the depth



c.) effect of erosion increases in function of the depth

Fig. 2.

D./ <u>During the process the deepest part of the dolina changes its place</u>

The shaft itself drains the water from its vicinity. In this surrounding the water leaves unsaturated the corrosion-zone of the dolina. This is the reason that this part of the dolina's bottom can not sink as fast as the other parts. Because of the slower development in the central part, one of the slopes of the dolina overpasses in sinking the former deepest part. So the very bottom of the dolina changes its place. This new place provides an opportunity for a new shaft to develop.

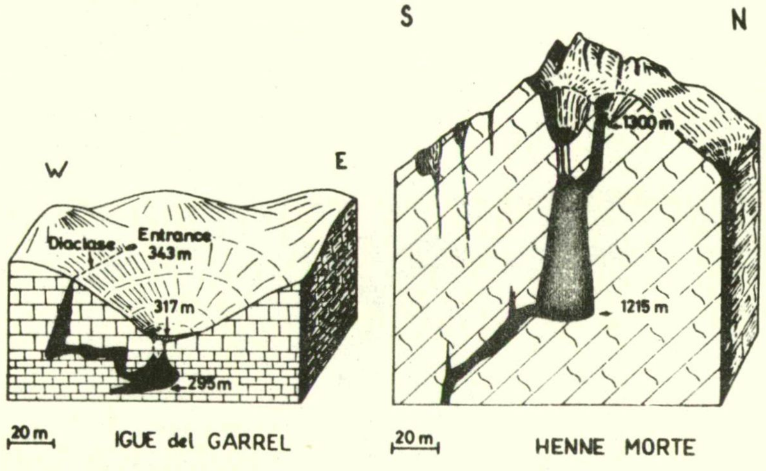


Fig. 3.

With the translocation of the centrum of the mother-dolina the entrance of the first shaft comes to the slope of the dolina. This trend of progress explains clearly: why even in homogeneous rocks the karst shafts have a step-like structure. This process seems to be probable in the case of some well-know karst-shafts /Fig. 3./.

E./ <u>The precipitation infiltrating on the surface of the dolina is sufficient to dissolve the lacking rock-mass</u>.

We should like to demonstrate that the recent natural factors are able to produce karst-shafts. For the sake of illustration we use data of the shafts in the "Alsóhegy" karst-plateau in Northern-Hungary.

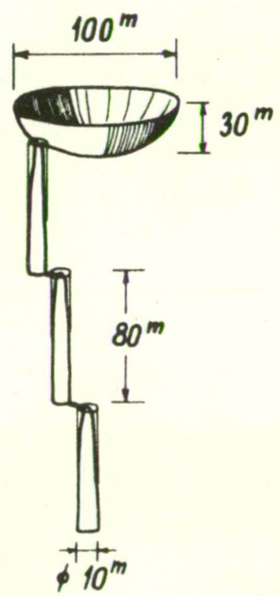


Fig. 4.

<u>The simplified data are as follows:</u>

Elevation of the plateau:	500 m above sea level
Elevation of the springs:	200 m above sea level
Average diameter of dolinas:	100 m
Average yearly precipitation:	700 m
Average Ca-ion concentration of the spring-water:	100 milligrams pro litre

The karstification is supposed to have its beginning in the Early Plaistocene, about two million years ago.

The deepest known karst-shafts attain nearly the level of the springs. The horizontal cross-sectional area of them is moderate: two or four times 10 m².

Starting from these data an average dolina-shaft system has the following dimensions /calculating that the dolina is a spherical section, and the shaft is a cylinder, Fig. 4./.

Horizontal surface of the dolina:	S_d /m²/ = 7,85 . 10^3
Volume of dolina:	V_d /m³/ = 1,32 . 10^5
Volume of shaft:	V_s /m³/ = 1,88 . 10^4
The system's lack of mass:	$V_d + V_s$ /m³/ = 1,50 . 10^5

It is noticeable that the volume of the dolina surpasses the volume of the shaft with one order of magnitude.

The 100 milligrams Ca in the spring-water is equivalent with 250 milligrams $CaCO_3$. That means that every m^3 of the spring-water contains 250 gramm dissolved rock-mass. As the specific wight of the rock is about 2,5 the volume-ration betwen the water and the dissolved rock-material is:

$$R = 1/10.000 = 10^{-4}$$

Supposing that the increasing of the dolina-surfaces in linear, and integrating the instant dolina-surfaces /Fig. 5./:

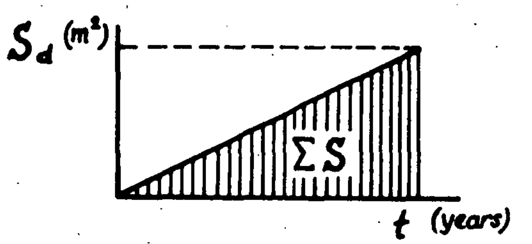


Fig. 5.

$$S = S_d \cdot t/2 = 7,85 \cdot 10^9 \ /m^2/$$

In only 200 mm water infiltrates yearly from the 700 mm precipitation on this surface, thus the total dissolving water-volume is:

$$W = 1,57 \cdot 10^9 \ /m^3/$$

The calculated lack of mass according to this water-volume is:

$$V_c = W \cdot R = 1{,}57 \cdot 10^5 \ /m^3/$$

So

$$V_c \approx V_d + V_s$$

that means that the calculated lack of mass is near to the real volume of the average dolina-shaft systems.

In the calculation we neglected several factors: the volume of shaft was supposed to be bigger than the actual, the infiltration seems to be higher than 200 mm/ /year, etc.

Summary

According to our hypothesis, the sinking shaft acts as a drain of its own dolina, and as a result their origin and development is common.

We try to outline the origin of the shafts as follows:

Before the rising, the surface of the karstic massive becomes flat by erosion. According to some new theories /Aubert, 1969/ the karstic plateau can develop after the rising of the massive, too. When arising, subvertical lithoclases can come into existence in the massive. On the favourable spots begins the development of dolinas. /Fig. 6/1/ The lithoclases at the bottom of the dolina make the zone of corrosion discontinuous; in this places the zone of corrosion sinks to a lower level /Fig. 6/2/.

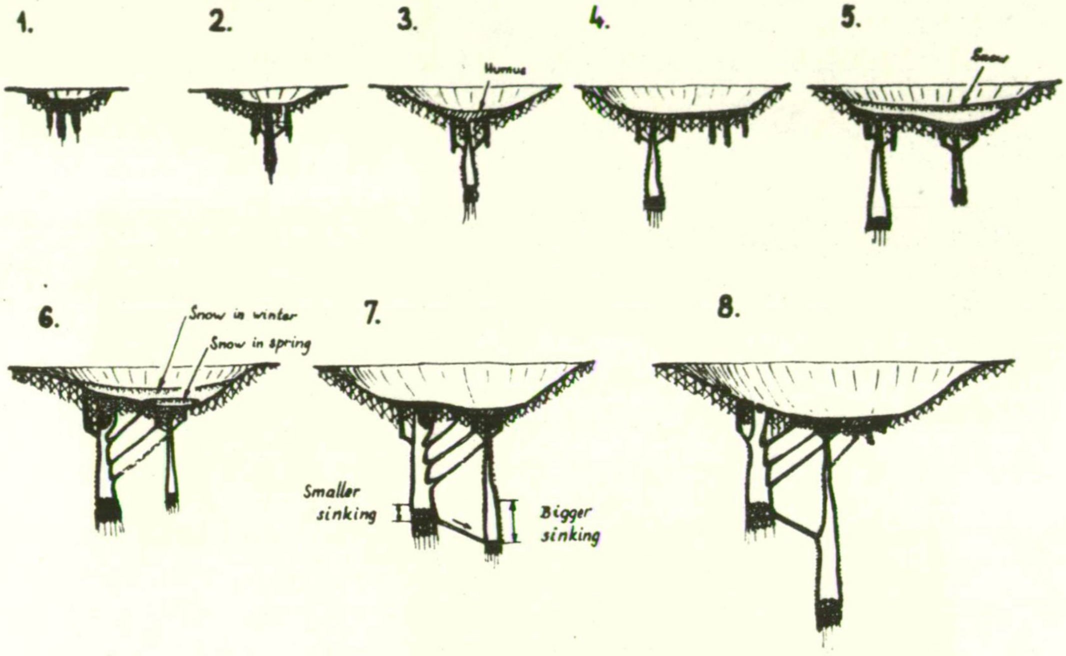


Fig. 6.

The sinking shaft drains the water from the dolina. For this reason the sinking of the dolina-bottom slows down in the vicinity of the shaft. /Fig. 6/3-4/. So the deepest point of the dolina necessarily changes its place, and under the new bottom a new shaft begins to develop. /Fig. 6/5./

The water of the second shaft is drained partially by the first cavity. In spite of this the deepening of the second cavity shall be more rapid as the base-area available for dissolution is smaller, the catchment-area is bigger, then in the case of the first cavity, and because of the accumulated snow and leaf-litter in the bottom of the dolina. /Fig. 6/6-7./ Therefore the new shaft overpasses in sinking the bottom of the first cavity, drains it and from this time on the new shaft sinks faster. /Fig. 6/8./

The water runs down on the walls of the developing shaft. At the foot of the wall the water dissolves the rock downwards and laterally. This is one of the reasons of the widening. Reaching 10-15 metres of depth, the erosion will fortify this effect. The rock-fragments, made by erosion can not leave the cavity through the lithoclases but accumulate and later it will be dissolved. So the cave is not increased /only shaped/ by erosion.

The development follows until the shaft reaches the base-level. Arriving at this level the primary dissolvent water begins to widen a horizontal cavity. In a permanently rising karst, thus in the case of sinking base-level, there is a low probability of the development of a passable horizontal cave originating from the shaft. If the rising stops, or if the base-level rises together with the plateau, the result of the process could be an important horizontal cave.

The authors believe this model of development to have a general validity. Anyway, in any individual case the applicability of this theory must to be investigated.

TEXT OF FIGURES

R E F E R E N C E S

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T. N a u m

LE VOLCANO-KARST DU MASSIF DES CĂLIMANI

Généralités

La littérature spécialisée mentionne l'existence de lapiés rudimentaires, imparfaits, sur des granites altérés et des gneiss sensibles à l'altération chimique, sur des basaltes, ou sur les escarpements des torrents de lave, sans expliquer leur genèse.

Différents travaux ont décrit les tunnele sousbasaltiques, cavités spectaculaires expliquées par l'accumulation massive de gaz ayant amené un gonflement de la lave vers l'extérieur /sous forme de calottes de lave ou hornitos/ et la formation de cavités de dimensions réduites dont le plafond est tapissé de stalactites de lave, ou par l'écoulement de la lave incandescente sous une croute solide. Des stalactites ayant l'aspect de draperies et des stalagmites se forment sous l'influence des gaz surchauffés par suite de la fusion de la lave suivie de recristallisation.

Nous présentons dans cette étude un phénomène karstique original, tant par sa genese gue par son allure qui semble unique à la surface du globe et n'a pas encore été étidie dans la littérature spécialisée.

Le Massif des Călimani appartient à la chaîne des Monts volcaniques néogènes /350 km/ comprise entre la zone cristallo-mésozoique des Carpates Orientales /E/ et le Néogéne du bassin de Transylvanie /W/. Au point de contact de ces deux unités géologiques, à la suite de l'effondrement du bassin de Transylvanie, sont apparues de grandes lignes de fracture qui ont favorisé l'apparition du volcanisme.

Le karst formé sur des roches éruptives est caractérisé par la présence des formes de surface /lapiés, alvéoles, etc./ développées sur des andésites pyroxéniques, ainsi que par l' silicifées, kaolinisées et limonitisées.

Formation des grottes

Le sommet Negoiul Romanesc est formé par une alternance d'agglomérats, de tufs non consolidés et de pyroclastites intensivement silicifiées et limonitisées.

Au début l'eau a circulé dans les fractures par infiltration, imprégnant le paquet entier de roches. Ensuite se sont formés de petits vides par enlévement des particules fines et par tassement dans toute la masse de dépots, ce qui a permis l'établissement d'une circulation souterraine de plus en plus concentrée et par conséquent un transport plus intense.

Les agglomérats et les cendres volcaniques mal consolidés constituant un plafond peu résistant, les vides existants ne se sont pas conservés. Par effondrement des plafonds ils se sont remplis de blocs, ce qui a donné lieu à la formation de nouveaux espaces au-dessus de ces blocs à la place des plafonds détruits. Dans une roche homogéne, par répétition du phénoméne, le vide initial aurait débouché en surface, ne laissant aucune trace de son existence.

Les conditions spécifiques de Negoiul Romanesc ont limité ce déplacement des vides vers la surface. Ceux-ci se concentrent à la partie inférieure des bancs de grande dureté formant un plafond résistant. En même tempa les circulations souterraines ayant suivi les petits vides, se localisent à ce niveau, en donant naissance à un petit cours d'eau souterrain.

Par érosion et par transport ce ruisseau souterrain, dans certains secteurs, élargit les cavités: dans d autres il les colmate.

Les grottes sont situées toujours à la limite intérieure de la zone silicifiée et limonitisée.

Les grottes sont basses mais /par contre/, très larges. Lorsque l'extension horizontale est grande, la plafond résistant de silice et de limonite peut s effondrer. Dans certains cas, l'effondrement entraine seulement la partie inférieure de la zone dure, en formant une grotte à l'intérieur de celle-ci. Dans cette grotte, les hydroxydes de fer contenus dans les eaux d'infiltration se sont deposés en donnant naissance a d'originales concrétions stalactitiques et stalagmitiques.

Les grottes présentent un aspect ruiniforme, le plancher étant couvert d'un chaos de blocs résultant de l'effondrement du plafond.

Un parallélisme relatif est évident entre le plafond et le plancher des grottes. À une grande accumulation de blocs sur le plancher correspond toujour une élévation du plafond/.

Les anciens cours d'eaux souterrains, actuellement secs, ont abandonné des dépôts de sable blanc, quartzeux, accumulé surtout dans les parties déprimées ou en pente douce, ainsi que dans la zone des points d'absorption.

Quelques - uns des petits vides initiaux se sont conservés dans la mosse des pyroclastites. Ils présentent des dimensions réduites variant de 1-6 m en longuer, et ne dépassant pas 1 m en hauteur.

On peut conclure que le karst souterrain du Massif éruptif des Călimani résulte de:

- La présence des voies de pénetration des eaux souterrain, jusqu au
- La présence de roches incomplétement cimentées, de faible cohésion, caractérisées par une porosité accentuée /bréches kaolinisées et cendres volcaniques/ favorisant la circulation souterraine des eaux.

- L'existence d'associations minérales permettant une dégradation physique rapide et le transport des composants en suspension /surtout des cendres volcaniques/.

- La présence d'horizons lithologiques rigides qui ont constitué les voutes des cavités formées dans la roche mal consolidée.

- L'existence d'une intense circulation ultérieure, concrétisée par des dépôts de sable d'anhydrite et de limonite.

Volcano - karst

1. Karst de surface

Les formes karstiques les plus simples /lapiés, alvéoles, alvéoles complexes, formes cylindriques et roches perforées/ s'observent sur les andésites pyroxéniques /andésites a augite et hyperstène/ des sommets les plus élevés qui jalonnent la grande caldeira des Călimani. Les formes karstiques superficielles se sont développées a la surface des niveaux supérieurs érosivo-structuraux de la coupole qui domine la plateau résiduel des Călimani.

La surface plane de ces niveax a favorisé la stagnation des eaux agissant aussi bien mécaniquement que par décomposition chimique sur les affleurements d'andésite pyroxénique.

Les eaux météoriques circulent à la surface des blocs et des laves andésitiques, en plaques horizontales ou légerement inclinées, d'épaisseur variable /de 2 à 3 m en surface, jusqu'à 1 m en profondeur/, qui présentent une intense altération, de nombreuses fissures et un clivage très réduit.

Les couches andésitiques ont une couleur rougeâtre due aux hydroxydes de fer. Les eaux stagnantes, à la surface des plaques, altèrent les feldspaths en les kaolinisent et séparent les éléments constituants /K, Ca, Na etc./. L'altération est favorisée par l'abondance des plagioclases /30 à 50 %/, la présence des mineraux mélanocrates /basiques/ comme les pyroxénes /15 %/ et les amphiboles, l'abondance des diaclases orientées dans tous les sens qui favorisent la pénétration des eaux météoriques dans la roche, l'apparition d'un faux clivage caractérisé par la séparation en plaques paralleles dont l'épaissur varie de 0,5 cm à quelques décimètres, la taille variable des cristaux constituants, leur contact et la natura du ciment.

De nombreuses formes négatives, représentées par des lapiés de longueur réduite, s'élargissent en rencontrant des alvéoles et des formes concaves cylindriques, résultant de ces processus.

Le Karst de surface est représenté aussi par des dolines d effondrement développeés à la surface des pyroclastites.

Ces dolines résultent de la kaolinisation avec silicification des pyroclastites, suivie de l'évacuation du matérie résultant et de la formation de vides provoquant le tassement et l'éboulement des depots de surface.

2. <u>Karst souterrain</u>

Le karst souterrain est représenté par trois grottes bien développées auxquelles s'ajoutent de nombreux vides de dimensions réduites.

Les deux premières grottes /Grotte du "Chaos" - 1' et Grotte des "Ruines" - 2/ ont des dimensiones considérables /1735 m² et 1180 m²/et sont situées à plus de 1709 m d'altitude.

La grotte du "Chaos" se présente comme une caverne immense, à deux compartiments: l'un orienté vers le sud-ouest, long de 48 m, et l' autre , vers le nord, qui après un parcours de 47 m, se rétrécit graduellement en torunant vers le sud-ouest sur 30 m.

La hauteur dépasse 6 m en certains points et se tient généralement autour de 3 a 4 m. Localement apparaissent des secteurs étroits, a l'allure de points d'absorption, par ou s'écoulent les eaux d'infiltration. Le plafond très irrégulier, avec de nombreux vides, diaclases et cheminées donne un aspect ruiniforme à certains endroits de la grotte. L'épaisseur du plafond est d'environ 50 m. Le sol est couvert d'éboulis épais de 2 à 3 m atteigeant 7 m.

Sur le plancher s'observent des dépôts de silice de 2 à 3 m d'épaisseur, de nombreux dépôts lacustres /kaolin - silice/ très meubles, des fragments de brèche volcenique dans un ciment limonitiques, des blocs de kaolin et de silice, durs, nombreux, légerèment limonitisés, dont la surface présente de nombreuses arabesques, aiquilles, tours, soit autant de formes mineures sculptées par les gouttes d'eau tombant du plafond. Sur le bord des blocs apparaissent des pendeloques isolées et de nombreuses draperies de kaolin et de silice. Dans le compartiment SW se trouve un bloc strié par les gouttes d'eau ayant ciselé de nombreuses colonnes tubulaires qui lui donnent l'aspect d'un orgue.

La grotte est traversée par de nombreux petits torrents dont les profils transversaux sont très varies; parfois tres étrits, alternant avec des secteurs plus larges à l'aspect de bassins.

Ces torrents sont alimentés par les gouttes d'eau du plafond, ou par des suintements. Ils disparaissent a travers les depots de silice, à la faveur des nombreux points d'absorption qui communiquent avec l'extérieur.

Dans les bassins s'observent de nombreuses microformes representées par de petits alvéoles, des vides cylindriques, de petits cratéres de 15 à 20 cm. de profondeur aux bords repliés et ornés d'arabesques bizarres sculptés par les gouttes d'eau.

La grotte des "Ruines" présente des hauteurs réduites comparativement à la précedente, les effondrements y sont très fréquents, les alvéoles sont petits et peu nombreux. Des breches volcaniques apparaissent, ainsi que des blocs durs et des croutes limonitiques a cristaux orthogonaux d'anhydrite.

Les deux grottes sont caractérisées par l'absence totale des concentrations limonitiques.

La grotte du "Palais de Chocolat" - 3 /184 m²/ s'élève vers le Nord à 1615 m et descend au dessous de 1612 m vers le SE. Elle présente des aspects très variés, avec de nombreux élar - gissements alternant avec des secteurs étroits, une salle large d'environ 11 m dans la partie centrale un et secteur étage en spirale vers le Nord. Elle est longue de 35 m, large de 0,40 m à 11 m. Sa hauteur varie entre 1-2 m, atteignant 2,5 m. L'épaisseur du plafond, 22 m est beaucoup plus réduite que celle des grottes précédentes. Les éboulements déj a signales s'observent, mais plus réduits.

Bien qu'elle soit la plus petits du massif des Calimani, cette grotte est remarquable par ses concrétions de limonite.

Le plafond, perçé de diacleses et de petites cheminees, est tapissé de stalactites, ne dépassent pas 5 cm. Il reseemble á une immense fourrure de mérinos avec de filets longs et tordus, de formes variées.

Les parois sont couvertes de draperies énormes, orientees verticalement et disposées sur plusieurs plans, qui descendent du plafond au plancher.

De même, sur les murs se voient de nombreuses concrétions semblables à des oreillers. La plancher est recouvert de blocs à la surface desquels se sont formées de nombreuses stalagmites qui, en général, présentent l'aspect de petits mamelons très aplatis. A la surface des blocs apparaisent des croûtes limonitiques. Le secteur nord est le plus beau car les concentrations limonitiques, de formes tres variées, ont recouvert la totalité des parois, du plancher et de la voûte du compartiment étagé en spirale. On y observe des stalagmites bien individualisées, de petits lacs avec des stalagmites en formation des stalagmites valonnées, des mamelons, des croutes et de tres belles draperies.

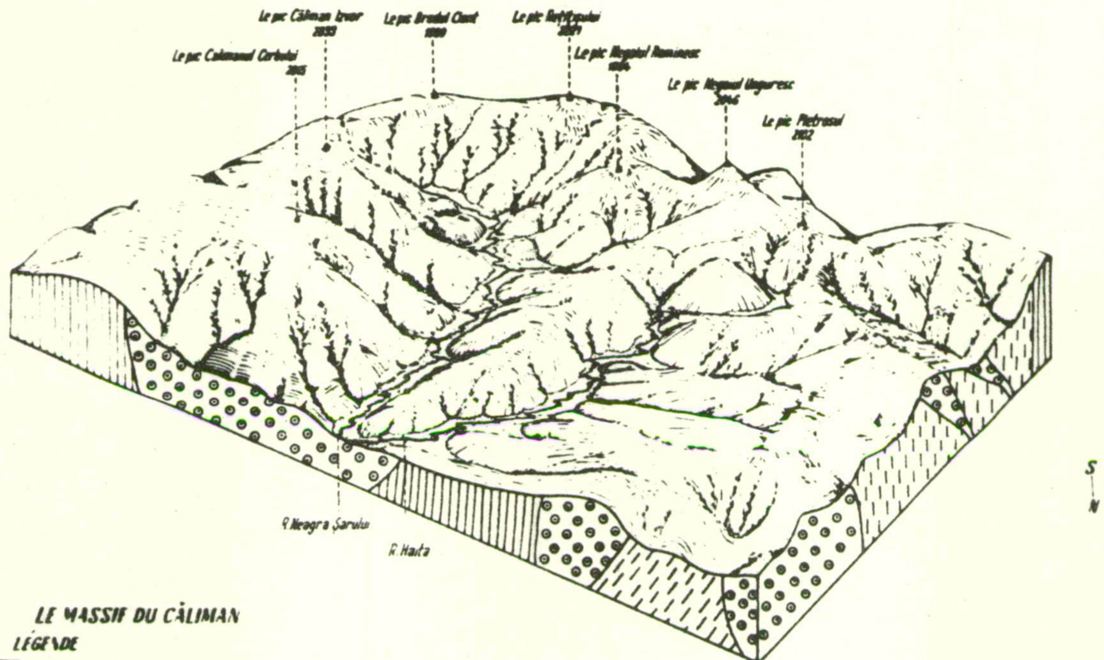
Cette présentation sommaire ne peut évoquer le décor féérique de cette grotte.

Origine des concentrations limonitiques

Toutes ces concrétions résultent de l'action des eaux d'infiltration, chargées de bioxyde de charbon, qui décomposent les minéraux ferrugineux en entraînant de fer dans les solutions bicarbonatées. Dans certaines conditions physico-chimiques celui-ci se dépose sous forme de concentrations limonitiques formées de différents hydroxydes à divers stades de déshydratation. Ce processus a été observé dans le secteur nord de la grotte ou apparaissent de nombreuses concrétions actives. A leur surface se trouve toujours une couche d'un gel de limonite pure. Par évaporation, ce gel détermine l'apparition de concentrations de limonite. Une partie de ce gel s écoule, et en tombant sur le plancher, forme des stalagmites et surtout des mamelons stalagmitiques car, contrairement à ce qui arrive dans le cas des solutions calcaires, l'évaporation est beaucoup plus lente, ce qui a comme conséquence un concrétionnement moins rapide. Les draperies et les croutes sont dues au meme processus sauf que les prémieres revetent les parois en totolité. L'intérieur des stalactites présente de nombreux canaux tubulaires, par ou circulé les eaux d'infiltration.

Conclusions

Le karst du massif éruptif des Călimani représente un phénomène original, explore, analysé et expliqué au point de vue génétique pour la première fois par les auteurs de cette communication qui ont la conviction d'avoir réussi à interpréter avec assez de justesse le mode de formation et le développement de ce type de karst, pour lequel ils proposent le terme de "volcano - karst".

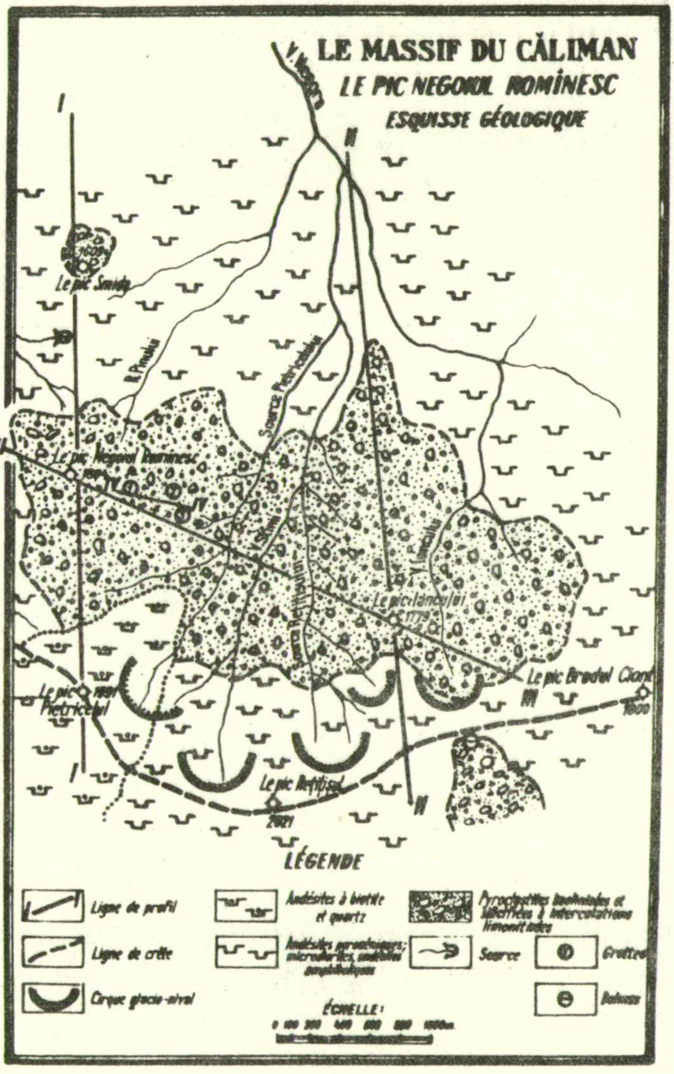


LE MASSIF DU CĂLIMAN

LÉGENDE

- Andesites
- Agglomérats andésitiques
- Pyroclastites à fragments d'andésites pyroxéniques

Cartograph A. Popescu


LE MASSIF DU CĂLIMAN
LE PIC NEGOIUL ROMÎNESC
ESQUISSE GÉOLOGIQUE
Le pic Smida
Le pic Negoiul Romînesc
Source Pietricelului
Le pic Iancului
Le pic Bradul Ciont
1900
Le pic Pietricelul
1981
Le pic Reţiţişul
2021
LÉGENDE
Ligne de profil
Ligne de crête
Cirque glacio-nival
Andésites à biotite et quartz
Source
Grottes
ÉCHELLE

D. R a d i n j a

CARACTÉRISTIQUES FONDAMENTALES DE LA KARSTIFICATION EN SLOVÉNIE /NW DE LA YUGOSLAVIE/

Pour le karst classique de la Slovénie sont régionalement caractéristiques les plateaux karstiques au relief intermédiaire plus bas, composé en majeure partie de couches imperméables tertiaires et autries. Ces rapports hypsographiques entre les reliefs karstique et fluvial attirent l'attention sur les caractéristiques morphogénétiques de base du relief entier.

À ces différences d'altitude il ne s'agit pas seulement de la dépendance de la stucture tectonique, mais bien plus de la dépendance de la composition pétrographique de la surface et des processus morphogénétiques conditionnés par le climat. Les rapports hypsographiques actuels du relief pétrographiquement différent s accordent en effet avec les processus morphogénétiques d'aujourd'hui, car la surface carbonaté dans le climat présent est plus résistant que les couches imperméables tertiaires et autres.

Pour les plateaux karstiques, il est en outre caractéristique que vers les bords ils sont de plus en plus aplanis. C'est pourquoi la découpure de la superficie au bord des plateaux est d'autant plus expressive et caractéristique.

A côté des aplanissements, au bord des plateaux sont interrompus aussi d'autres traits du relief; tous cependant restent tout simplement suspendus au-dessus du voisinage plus bas.

La découpure et la suspension du relief en plateau font observer que la superficie calcaire s'est formée en liaison large et fermée avec le voisinage imperméable, lorsque la surface carbonaté et non carbonaté étaient encore à la même altitude, et en bien des endroits la superficie imperméable était même plus élevée que la superficie karstique. Il est donc évident que la superficie des plateaux karstiques d'aujourd'hui s'eset formée dans des rapports hypsographiques essentiellement différents de ceux d'aujourd'hui.

Des traces diverses appellent l'attention sur les rapports d'altitude autrefois différents entre les superficies karstique et imperméable. Parmi les formes de relief, cela est indiqué surtout par les vallées karstifiées qui traversent les plateaux karstiques. La genèse des vallées sèches est peut-être contestable à la lumière des processus érosifs et corrosifs. Il est cependant incontestable que les vallées kartifiées ont fait partie du relief fluvial ancien qui embrassait une superficie pétrographiquement différente et s'étendait au-dela des couches perméables et imperméables. Les vallées transversales délaissées ne témoignent pas seulement des rapports hypsographiques, mais font observer aussi la liaison ancienne entre les superficies karstique et fluviale.

Les rapports d'altitudes correspondants et la liaison de ce relief sont attestés aussi par les traces de l'accumulation fluviale qui s'est conservée sur la surface karstique jusqu'à nos jours memes.

Ces traces ne se trouvent pas seulement dans les vallées sèches, qui sont si caractéristiques pour le karst classique, mais encore sur le reste de la superficie karstique, surtout sur les terrasses et les aplanissements. Les recherches faites en Slovénie au cours des dernières années ont découvert des traces d'accumulation fluviale presque dans toutes les régions karstiques. Il y a tant de restes de ce genre que nous pouvons les ranger parmi les traits caractéristiques du karst classique /alpin et dinarique/. Mais ici nous devons considérer que sur les plateaux karstifiés ne s'est conservée qu'une partie insignifiante de l'accumulation. Ne se sont conservés que les matériaux fluviaux qu'en raison de leur composition silicatée la corrosion n'a pas pu anéantir, tandis que les additions carbonatées sont dissoutes. Les rested d'accumulation sont de ce fait réduits quant à leur étendue et surtout quant à leur structure. Il est donc compréhensible qu'il n'y a parmi eux presque exclusivement que des galets de quartz et du sable. Les graviers silicatés moins purs sont, par contre, fortement altérés.

Les matériaux fluviaux, qui se sont conservés sur la surface karstique, sont très importants pour la compréhension de la morphogenèse karstique. Il faut cependat être prudent dans l'interprétation, parce que la genèse de ces matériaux est très différente. Les études effectuées montrent en effet que les galets de quartz sont d'origine hétérogene et, si nous n'en tenons pas compte, les conclusions peuvent etre tres différentes et erronées.

Par endroits, les matériaux fluviaux se composent de galets de quartz qui ne sont rien d'autre que le reste la de couverture tertiaire ancienne, qui recouvrait les calcaires. Des conglomérats décomposés, qui étaient parmi la couverture, se sont détachés les graviérs silicatés qui se sont maintenus à la superficie calcaire pendant tout le cours de la karstification. Ces graviers n'ont évidemment pas de liaison directe avec la genese de la superficie karstique. Ils ont cependant leur importance, parce qu'ils indiquent une plus grande extension des sédiments teriaires et évidemmet la couverture imperméable qui recouvrait les calcaires.

Plus importants du point de vue morphogénétique sont les restes fluviaux qui furent apportés du voisinage imperméable. Ces sédiments allochtones sont aussi les plus nombreux sur la surface karstique. Ces matériaux proviennent en majorité dans les régions karstiques subméditerranéennes des couches de flysch voisines, dans les régions subpannoniennes des différents sédiments néogènes et, dans les régions karstiques de la Slovénie intérieure, ces restes proviennent pour la plupart des couches paléozoik /conglomérats et grès/.

L'accumulation fluviale allochtone aussi est d'origine différente. Moins importante du point de vue morphogénétique est celle qui s'est formée par la démolition et l'enlèvement des couches clastiques grossières. La deuxième partie de l'accumulation allochtone se compose des galets qui se sont reformés à partir des roches siliçatées compactes /par ex. les galets des couches de flysch/. Il s'agit ici des matériaux qui se sont formés lors du transport des matériaux silicatés et se sont en partie transformés appellen l'attention sur les processus fluviaux et autres, qui se sont déroulés à la superficie calcaire elle-même.

La plus importante est cependant l'accumulation fluviale qui s'est formée à l'intérieur des régions calcaires. Il s'agit de matériaux fluviaux autochtones qui se sont formés à partir des rares intercalations silicatées, qui se trouvent entre les calcaires et les autres roches carbonatées /par ex. les silex et les limonites/. La signification morphogénétique des alluvions autochtones réside dans le fait qu'il s'agit de matériaux qui se sont formés exclusivement sur la surface calcaire. Ils nous révèlent les processus qui ont créé la superficie karstique. Ici, il est tout particulièrement important de noter qu'à côte des galets silicatés se sont formés aussi des galets carbonatés. Ces derniers ont cependant été détruits plus tard par la corrosion. La présence des galets carbonatés est attestée surtout par la porosité du conglomérat, dans lequel se sont conservés seulement les graviers silicatés, tandis que les graviers carbonatés ont été lessivés. C'est de là que provient la porosité caractéristique des restes de conglomérat, qui se sont conservés au coeur du Karst même.

Les restes de l'accumulation fluviale autochtone sur la surface karstifié prouvent qu'à la superficie calcaire se sont affirmés différents processus morphogénétiques, parmi lesquels il y avait sans nul doute aussi des processus fluviaux ou érosifs. En connexion avec cela se pose la question de savoir quelle part l'érosion à eue dans le processus morphogénétique entier, qui s'est déroule à l'époque pliocene dans les régions calcaires du karst classique, surtout par rapport à la corrosion. Il est clair cependant que l'interprétation érosive ou corrosive du karst classique ne peut plus être posée d'une maniere alternative, mais tout au plus complémentaire.

En Slovénie, les restes de l'accumulation fluviale se sont conservés des plateaux karstiques les plus élevés au coeur des Alpes Juliennes /Komna/, où ils se trouvent à une altitude d'environ 2000 m, au karst le plus bas ou bord de la Plaine pannonienne /karst de Novo mesto/ et de la mer Adriatique /Karst proprement dit/, où ils sont à une altitude d'à peine 200 ou 300 m.

L'extension sur la surface karstique des restes fluviaux conservés montre plusieurs traits caractéristiques. Ces restes sont les moins nombreux sur les plateaux centraux plus élevés de la Slovénie intérieure, et les plus nombreux dans les régions karstiques plus basses des bordures subméditerranéenne et subpannonienne. Le volume des galets et du sable augmente donc de la Slovénie intérieure vers la bordure tertiaire. C'est en cette direction qu'augmente aussi la variété de l'accumulation fluviales.

Les matériaux paléofluviaux se sont conservés d'une maniere différente sur la surface karstique. Par endroits, ils ne se composent que de rares graviers dans l'argile karstique, tandis qu'ailleurs sur la surface karstifié il y a plus de galets de quartz, surtout dans les vallées sèches, et sur les aplanissements ils sont surtout dans les dolines. Par endroits, les gouffres karstiques aussi sont comblés de galets de quartz. À la bordure pannonienne, dans la surface karstique il y a de nombreuses poches de sables quartzeux purs /karst de la Basse Carniole/ en une quantité telle qu'on les exploite industriellement /sables de fonderie et de verrerie/.

Les galets de quarz, conservés sur la surface kartique, sont partout bien arrondis. Selon la méthode de Cailleux, il s'agit de l'arrondissement qui est caractéristique pour les sédiments qui se sont formés en climat chaud. Le pollen aussi, qui s'est conservé parmi les matériaux paléofluviaux /dans l'argile et les grès/ indique que l'accumulation fluviale s'est déposée en période chaude.

Dans les régions karstiques, les restes fluviaux sont localement sursédimentés en raison de la karstification postérieure. Comme les dolines sont sans nul doute d'âge pléistocène, il est évident que les restes fluviaux n'ont été dénudés que plus tard en dépressions karstiques.

Les restes de l'accumulation fluviale sur les plateaux karstiques d'altitudes différentes ne témoignent pas seulement de la liaison morphogénétique de la superficie calcaire et du voisinage imperméable, mais encore du fait qu'à l'époque pliocène les couches imperméables tertiaires et autres étaient en bien des endroits plus élevées que la surface calcaire. Nous attribuons un tel rapport hypsographique entre les calcaires et le voisinage imperméable avant tout au climat pliocène chaud et humide, dans lequel la corrosion intensive abaissait plus vite la superficie carbonatée. Par contre, a l'époque quaternaire plus froide, surtout dans les périodes glaciaires, ce rapport s'est détruit, parce que la forte décomposition mécanique la surface avec l'érosion renforcée abaissa plus vite les couches tertiaires alors moins résistantes. Ainsi, les rapports hypsographiques centre les superficies carbonatée et non carbonatée furent toujours en accord avec les processus morphogénétiques conditionnés par le climat. C'est pourquoli il y a eu relativement peu de relief inversé. Un exemple manifeste de ce genre de relief sont les hauteurs de flysch au bord du Karst proprement dit /Brkini/. Nous l'interprétons comme un reste des couches de flysch autrefois bien plus étendues, qui s'élavaient au-desus des masses calcaires voisines /Nanos, Hrušica, Javorniki, Snežnik, Kras proprement dit/. Les processus exogènes conditionés par le climat étaient plus déterminants que les processus tectoniques au moment où le relief se formait. En ce qui concerne l'âge, nous rangeons ce relief dans le pliocène plus jeune et le pléistocène.

Les traces de l'accumulation fluviale conservées sur les plateaux karstiques ne témoignent pas seulement des rapports d'altitudes correspondants, mais encore d'une composition pétrographique de la surface différente. Au pliocène, le relief se composait de bien plus de couches tertiaires. Cela nous est attesté aussi par les restes de dénudation de ces sédiments, qui se sont conservés sur le relief fluvial et aux bords des plateaux karstiques /Trnovski gozd, Nanos, Snežnik, hauteurs du Posavje, etc./.

La composition pétrographique de la surface ne s'est pas transformée seulement par suite du soulèvement tectonique et de la dénudation revivée, mais en premier lieu en raison des changements climatiques. Les études effectuées montrent qu'au pléistocène se sont plus vite abaissées les couches tertiaires et imperméables en général. Dans cette période, les vallées se sont approfondies d'environ 150 m, alors que la superficie calcaire s'abaissait bien plus lentement. C'est pourquoi, vers la fin du pliocène, et surtout dans la période suivante du pléistocène, ler régions calcaires se sont transformées en des plateaux de plus en plus expressifs.

En raison des processus érosifs et corrosifs déviés climatiquement, aux périodes pliocène chaude et pléistocène froide se sont donc transformés à la fois aussi bien la composition pétrographique de la surface que le rapport d'altitude entre les roches de part et d'autre. Mais les deux phénomènes avaient une signification déterminante pour le développement du relief karstique.

L'éloignement progressif de la couverture tertiaire et la dénudation du fondement carbonaté, ensemble avec les changements climatiques et les rapports hypsographiques modifiés entre les reliefs karstique et voisin, étaient parmi les traits les plus caractéristiques qui accompagnerent la karstification du karst classique en Slovénie.

Le trait fondamental suivant de la karstification est le fait que les calcaires dénudés étaient largement entourés et revêtus de couches imperméables. Dans les calcaires ainsi fermés, la circulation souterraine de l'eau ne pouvait pas non plus se déployer, sans considérer que dans la période pliocene chaude il n'y avait pas de conditions convenables pour la corrosion en profondeur, parce qu'alors se déroulait la corrosion intensive et à la fois rapide qui d'épuisait déjà en surface. Evidemment la corrosion en profondeur ou le creusement des calcaires à cette période était empêché aussi par l'hypsographie d'alors avec des calcaires plus bas et un voisinage imperméable plus élevé. Dans de telles conditions, l'hydrographie superficielle s'est tout le temps maintenue sur la surface carbonaté. C'est pourquoi la superficie calcaire au pliocène à été transformée par les processus qui réunissaient l'activité corrosive et érosive a la fois. L'érosion des eaux superficielles dirigeait la corrosion, en sorte que les régions calcaires resterent tout le temps ouvertes. Les conditions pour l'aplanissement des calcaires étaient alors aussi les plus favorables. Il en arriva à des formes superficielles fermées /des dolines, uvalas et poliés karstiques/ et là à perforation des calcaires seulement à la période pléistocene froide, lorsqu' avec l'abaissement du voisinage imperméable les calcaires furent largement ouverts et qu en raison de son cours long la corrosion alla en profondeur. Nous estiomons que dans la période où sur la surface karstique coulaient les eaux superficielles, donc à la phase antékarstique, la corrosion était plus intensive qu'à la période pléistocene. Donc, l'érosion et la corrosion ne se substituaient pas dans le temps et leur évolution, mais elles s'entrelacaient directement à la période pliocène.

En raison de l'alternance des calcaires et des couches imperméables, les régions karstiques particulières étaient largement revêtues par la bordure imperméable et, par là, fermées, endiquées. L évolution de la superficie karstique dépandait donc à ce point de vue aussi directement de la bordure imperméable. Et l'évolution du relief normal dépendait aussi du voisinage karstique. La liaison réciproque et la dépendance de l'un et l'autre relief étaient plus grandes que nous l'estimons ordinairement, surtout parce que nous étudions le relief karstique d'une manière trop isolée. Les parties carbonatées et non carbonatées de cette superficie se sont développées autrement que ce serait le cas si elles avaient été séparées dans l'espace et non liées dans leur évolution; pour cela le relief entier s'est développé autrement.

Sur la surface calcaire, on peut en effet suivre tout le temps les effets fluviaux et autres d'un voisinage différent du point de vue pétrographique, et sur ce voisinage, les influences morphogénétiques de la surface calcaire. Ici il ne s'agit pas seulement des particularités du relief au contact pétrographique direct, mais le relief de contact au sens plus large englobe les deux espèces de régions en entier. Cela ne vaut pas seulement pour le karst que les eaux traversaient et qui se trouve au milieu des couches imperméables, mais encore pour le karst qui avait un voisinage imperméable seulement d'un côté, soit d'arrivée soit d'écoulement.

Eu égard au développement hypsographique et à l'ancienne liaison hydrologique entre les calcaires et le voisinage imperméable, le développement du karst classique et particulièrement du relief de contact présente les caractéristiques suivantes.

Le premier type sont les "calcaires des sources", qui se sont développes au-dessus du voisinage imperméable. Sur ceux-ci il y a en général moins de superficie plane et les éminences prédominent, car sur ces calcaires on ne voit que les effets des eaux autochtones. Il y a plus de terrain plat aux endroits où les eaux calcaires ont exécutés des aplanissements de bordure à la hauteur du voisinage imperméable. C'est pourquoi la superficie est en entier suspendue vers la voisinage.

La caractéristique des calcaires des sources est la série des formes à pignon: des vallées, des uvalas et des poliés karstiques. Typiques sont surtout les vallées suspendues. Les aplanissements et les formes approfondies indiquent la hauteur de l'ancien revêtement imperméable.

Les traces d'alluvions fluviales sont exceptionnelles sur les calcaires des sources. Si elles sont conservées, elles sont autochtones.

Le deuxième type sont les "calcaires des confluents". A cause des anciennes eaux allochtones, sur ceux-ci il y a plus de superficie plus basse et aplanie. Au bord extérieur des alluvions allochtones, les eaux du voisinage imperméable ont corrodé et dissocié les éminences calcaires. Des aplanissements et des terrasses se sont formés, qui - en comparaison avec les calcaires des sources - avaient un écoulement d'eau opposé et qui sont de ce fait inclinés de la bordure imperméable vers le noyau calcaire. Avec l' abaissement différencié des deux aspèces de roches, sur les calcaires se sont développées de vallées aveugles, des poliés karstiques de bordure et des terrasses de bordure.

Le troisième type sont les "calcaires transversaux", où il y a le plus de superficie plane. Les aplanissements sur les calcaires sont ordinairement continus. La superficie est inclinée dans une direction. Pour ces régions sont caractéristiques les vallées transversales et les cours d'eau transversaux qui dirigeaient l' aplanissement de la superficie. Sur les calcaires transversaux il y a aussi le plus de restes de l'ancienne accumulation fluviale. Parmi eux il y a certes le plus de matériaux allochtones, mais il y a aussi une accumulation autochtone.

Les régions calcaires sont encore aujord'hui dans la position qui correspond aux diverses phases d l'évolution passée. Il y a même des exemples qui sont caractéristiques pour l'hypsographie pétrographique pliocène avec un tertiaire plus élevé et des calcaires plus bas. Mais dans la plupart des cas les conditions actuelles sont telles que le bord imperméable est abaissé et que les calcaires du karst classique sont largement ouverts.

Avec la formation des différences d'altitudes entre les calcaires et le voisinage s'est relachée la liaison morphogénétique directe des deux espèces de régions. Ainsi il en est arrivé aussi à des aplanissement acorrélatifs aux bords calcaires. La stagnation des masses calcaires et la destruction intensive du voisinage imperméable ont mené à la squelettisation du relief.

Par suite de l'abaissement corrosivement uniforme de la surface, sur le karst classique se sont conservées les formes plus anciennes, héritées, qui s'étaient à la période pliocène chaude et qui présentent les traits du karst tropical. Dans les dépressions karstiques démembrées et fermées et la porosité des calcaires se manifestent les caractéristiques du karst périglaciaire. Dans l'entrelacement des deux formes résident donc les principales caractéristiques du karst classique.

A.L. S a n t o y o

A REMARKABLE LAPIAZ TOPOGRAPHY IN THE SOUTH OF CENTRAL MEXICO

At the western part of the State of Mexico, almost at the border with the State of Michoacan, 110 kilometers west-southwest of Mexico City there is a picturesque town: Valle de Bravo. It is located at one side of the bottom of a depression with more or less an elliptic shape and oriented southeast to northwest.

Just by the town at the lowest part there is an artificial lake, seven kilometers long and two kilometers wide as an average. This lake is part of one of the main hidroelectric systems in the country, the "Miguel Alemán".

The relief around the lake is mountainous with mostly moderate slopes.

Massive limestone is the base structure of a large area which includes the one mentioned here and volcanic material predominates at the surface. Near the lake metamorfic rock from old sediments is found.

In aerial photographs taken about 25 years ago it can be seen that before the dam was built the bottom was a cultivated flat plain. A small meandering river ran along the plain. Some other streams did not reach it and they ended in swallow holes.

There are also some springs which indicate the circulation of underground water in the region. One of them is two kilometers from the northwest end of the lake and about 100 meters below its level. Another one is north of the lake and somewhat above its level.

Beside the lake there is a hill of massive limestone localy known with the name of "La Peña". On top of this hill there is a well developed lapiaz topography.

All these characteristics make us think that the lapiaz is on the hum of a polje whose evolution was interrupted by volcanism.

Even though as it can be seen, this region has some very interesting aspects in its morphology, this paper will deal only with the lapiaz topography.

The main lapiaz forms are striae on the outer surface of the rocks. These striae are parallel among them and sometimes very uniform. They generally measure two to three centimeters wide and run vertically. Where the rocky surface is smaller or where a step is formed, two or more striae can get together and form a bigger one, on the contrary, if the surface increases, the crest between two striae can branch in two.

The mêchanic action and chemical dissolution of the rain water can be clearly seen on the striated rocks, that have a hole on the top where water acumulate and is dislodged by a lateral anlarged stria, or by several that have united forming a bigger one. /Photo 1./ In some of the rocks a well defined drainage system can be seen.

The limestone besedes being massive is intensely fractured and the water that penetrates in the vertical fractures accumulates in the bottom where it produces a stronger dissolution on the sides. The evolution of these fractures divides the rocks forming two isolated ones. /Photo 2./

Along the bedding planes small cavities and holes are formed by dissolution, which are alined even if the rocks have remained isolated one from the other.

The top of the hill is constituted by a series of truncated pinnacles, which are scarse further down.

The pinnacle shown on the picture /Photo 3./ is hollow with a lateral entrance in which aproximatly 10 persons could fit standing up.

It can be noticed that some of the walls of the rocks are very thin, in others the interior is hollow so that if the rock is hit gently with a metallic piece, a short and weak sound, similar to a bell is produced.

Some of the rocks have cilindric holes of different sizes in them, which leads us to suppose that they where made by stalks and roots of plants that do not exist any more.

It is evident that dissolution process which has left all these forms is not recent.

The vegetation that is now found there is rachitic and the shrubs break the rock as they grow. Only between their roots small dissolution if found, but it is not sufficient to leave space for them to grow.

This indicates that besides a lack of organic acids, the air does not have the necessary elements as an abundant precipitation and great quantities of carbone dioxide, given by the plants, to help dissolve the rock.

On the other hand such a superficial modelling as the one given by the striae cannot be too old. It is possible that the last phase of development of the dissolution phenomenon and the formation of striae took place during the pluvial epochs of the Pleistocene and that the forms have preserved after wards under a layer of sediments. The characteristics of the hill are those of an exhumed relief. This is due to the scarse development of debris at the base, the lack of gullies in them and the breaking of the slope that limits it with the flat part. Besides the upper part which is more exposed to weathering is the one which presents destruction in the lapiaz forms.

A.V. S t u p i s h i n

PLAIN KARST AND THE BASIC LAWS OF ITS DEVELOPMENT

Karst is a wonderful phenomenon of our planet. Being the product of complex hydrochemical processes under certain natural conditions, karst presents a complex geological history of the development of the earth crust in the platform and fold structure of the continents, a characteristic system of subsurface cavities, frequently arranged in a stage pattern in a geological section. The amazing and grandiose systems distinguishing the karst landscapes of Europe, North America and Asia are particularly striking.

The global spread of karst, its occurence on differnt continents, in different climatic-landscape zones, at different altitudes, from low-lying planes to high altitude regions is accounted for by the wide spread of soluable rock, both exposed and buried: limestone, dolomite, chalk, marble, gypsum, anhydrite, mineral salts /salt karst/. According to G.A.Maximovich /1963/ the rock subject to karst processes amounts to up to 40 million km² or one third of land.

On the earth surface karst processes form a characteristic karst relief of the surface and subsurface run-off, a peculiar geological composition of rock with great masses of breccia. Karst cavity filling contains valuable and various ores, rare mineral deposits. Oil, natural gas, bauxite and other deposits tend towards karst rock.

The typological peculiarities of karst in mountain and plain areas were described by L.Savitsky /1909/. He distinguished two types of karst in Western Europe: Mediterranean and mid-European or exposed and mantled, respectively. These terms have been widely used in literature. A closer scrutiny of the typological definitions of karst, however, reveale their limitations.

If we take into account the fact that Mediterranean karst is an example of mountain karst, while mid-European reflects the features of plain karst, it is quite logical to accept the following names of geomorphological types of karst: mountain and plain karst /Stupishin, 1967/.

The author suggests geomorphological classification of karst with an account made for 16 features: geostructural, morphometric, lithological, karst rock thickness, the degree of karst deposit exposure, the depth of karst rock bedding, age, the age regenerations of karst, the stratigraphy of karst rock, the activity of karst processes, climatic, the degree of flooding /hydrological/, morphological, geomorphological, botanical, evolutionary /Stupishin, 1967, pp. 22-24/.

This paper deals with the singularities of plain karst and the main laws of its development. I.P. Gerassimov and Ya.A.Meshchryakov /1967/ have shown the principal features in the development of the Earth's relief. They distinguished two principal morphostructures of land, viz., the morphostructure of plain-platform areas and that of mountains areas /orogenic/.

The theories put forward by I.P.Gerassimov and Ya.V. Meshcheryakov /1967/ on land plain and mountain morphostructure confirm from the geomorphological viewpoint the suggested geomorphological classification of karst.

Plains constitute over 64 per cent of land, primary plains formed by practically horizontal layers of sedimentary rock accounting for 47 per cent, while denudation and socle plains representing peneplain territories of old folded structures account for 17 per cent /Gerassimov, Meshcheryakov, 1967/.

In the Soviet Union karst in socle denudation plains occurs in the Kazakh Preublic /Stupishin, 1968/. It is old and has been investigated in connection with the evaluation of the bauxsite content of the old karst relief of Central Kazakhstan. "In the great plains of the earth, however, stratum and recent accumulative surfaces predominate rather than peneplains. Their flat character reflects the platform type of relief-forming rock position" /Gerassimov, Meshcheryakov, 1967, p. 19/.

Mantled karst /as understood by Gvozdetsky, 1954, p. 330/ is typical of plain karst, since karst rock is usually covered by non-karst deposits of various lithological composition, origin, age and thickness. However at tectonically elevated spots small areas of exposed and turf-covered karst may occur.

Although the covering deposits are not subject to karsting, taey reflect with sufficient clarity the existence of subsurface karst developing in soluable rock. Its occurence is manifested on the day surface by various holes: sink holes, cavities and, often, by solution lakes. In rare cases karst rock is exposed in the hole walls. Thus the so-called "reflected karst" is typical of plain karst /Stupishin, 1967/. The term "reflected karst" stresses the dependence of surface hole shape on the subsurface karst, mantled in the case of plain karst by non-karst cover deposits of considerable thickness.

A relatively small thickness of the upper rock stage is characteristic of plain karst. It is determined by fluvial downcutting /normally 40-60 m in the Volga-Kama case/. This thickness of karst rock determines the insignificant depth of sinkholes.

Karst frequently occurs in river valleys, this phenomenon complicating the surface of aggradation terrace filling. Karst is particularly frequent at terrace joints and between the upper terraces and water divide slopes. In terrace surface areas karst occurs in superimposed erosion hollows, shallow valleys, gorge systems, forming in some places solution lakes, up to 30-40 m deep /Middle Volga region/. Karst forms are also observed on right bank slopes of river valleys, where covering non-karst deposits are washed considerably and soluable jointy rock comes close to the surface. Longitudinal fracture trenches of gravitational karst origin are typical of such slopes. These trenches may be dozens of kilometres long, dozens of metres wide and up to 40 m deep /Middle Volga region, Angara region, Eastern Siberia/.

In the extraglacial zone of the Russian Plain stratum elevated step-like denudation plains /erosion-denudation planation surfaces/ are common. In these plains water-divide and water-divide-slope karst frequently occurs. It is characteristic of gentle and long slopes which face a river valley. In the case of the washing out and small depth of non-karst deposits on slope surfaces linear zones of hole karst forms /sink holes, cavities/ can be observed. It has been noted that the spread of karst cavity chains on slope surfaces is often associated with the jointing in soluable mountain rock.

Karst also occurs in accumulative low plains. This is a frontal apron karst in the Russian Plain /"Russian Polessie"/ which is characterized by numerous solution lakes as well as by the combination of karst, suffosion and aeolin forms of relief.

Thus in the Russian Plain which is considered to be a typical sphere of the spread and development of plain karst three main types of karst landscapes should be distinguished: I/ karst landscapes of river valleys; 2/ karst landscapes of old denudation planation surfaces; 3/ karst landscapes of Anthropogen superimposed accumulative plains. Each of the distinguishable karst landscapes is characterized by morphologo-hydrographic and landscape singularities, by a combination of karst objects.

In karst areas one may come across the following karst types of relief: 1/ karst bed-land which is a basin-type relief with outlying hills, the outliers of primary surface; 2/ karst hummocky topography with ringed karst trenches. It is found in small tectomic structures /brachy-anticline/, composed of joint, soluable rock. Brachy-anticlines complicate the structure of platform ramparts, e.g. the Vyatka or Oka-Tsna; 3/ karst-valley topography is characterised by the regenenation of surface drainage, its transformation into a subsurface one, by the complication of a valley floor by karst cavities with sinkholes, by the presence of slope gravitation-karst belts and trenches; 4/ karst-ravine-gorge topography represents regeneration under the influence of the karst of small erosion forms /ravines and gorges/. Blind karst ravines and gorges having basin form which constantly recurs are typical; 5/ karst-lake topography. It is characterised by the presence of a large lake basin /one or more/ with steep banks complicated by karst cavities of the funnel type.

Each of the distinguishable karst topographies is characterised by local geographical landscape singularities.

Favourable orographic conditions and rugged plain topography in humid climate contribute under the conditions of karsting to the infiltration of a considerable part of surface drainage. The insignicant tiltin of soluable rock, normally constituting a few dozen minutes contributes to the development of karst over large areas. However the mechanism of karst processes is considerably complicated by the presence of non-karsting cover deposits which are subject to stoping, subsidence and washing-out over the sink centres and along the joints into karst cavities.

Karst in plains is subjected to the structural pattern of rock. It is confined to the platform deformation of sedimentation layers. It normally occurs within positive rampart structures /placanticlines/ which are characteristic of anteclises or large positive platform structures. Easily soluable rock: limestone, dolomite, gypsum, anhydrite is exposed or lies close to the surface within the limits of the Oka--Tsna, Vyatka-Volga, Soka-Sheshma, Zhiguli Ramparts. It is stripped in river valleys. Karst disappears in the zones of tectonic strata warping due to the overlapping of karst rock by the clastic deposit layers of considerable thickness. Besides, the low surface of tectonic sag is characterised by the downcutting of the river system dissecting the surface layers.

The analysis of the spread of karst within the limits of platform structures and ramparts testifies to the unevenness of the territorial spread of karst which more frequently develops on the slopes of the positive structures of the third order /brachyanticlines/ complicating the structural field of ramparts. As many as 12o karst holes /bedding caves, cavities/ per 1 km² have been observed /TASSR, MASSR, Gorky Region, etc/. Anticline structure slopes of the lower order are composed of jointy carbonate-gypsum deposits of the Kazan stage of the Perm system. The favourable strata gradients and increased jointiness of soluable rock facilitates the active development of subsurface and surface karst on the sides of tectonic structures. The area of these structures is found to be 50-70 km² at the relative elevation of the arch of up to 50-70 m. An important factor for the development of karst within the limits of small structures is the downcutting of modern or old river valley structures.

The lithological singularities of karst rock section are vital for detecting the strata in which active karsting takes place. In the east of the Russian Platform /Middle Volga region/ there are the following variatins of combined sections of karst rock: I. Homogeneous carbonate section composed of limestone or dolomite strata. Karsting is confined to the most readily soluable stratum, e.g. "sugar-like-limestone" /Zhiguli/. This stratum is affected by cavities /caves, grottoes/. 2. Heterogeneous carbonate section composed of the alternating strata of dolomites and limestones. Limestone being more readily soluable, particularly when it has macrocrystalline structure, is affected by cavities. This carbonate breccia is formed in the geological section, the dolomite breccia being cemented by secondary calcite, appearing as a result of the solution of the macrocrystalline limestone layers /Samara Bend/. 3. Carbonate-sulphate section composed of jointy limestones or dolomites overlaying waterproof gypsums. In the case of a deeply downcut river valley /the Oka, the Volga, the Kama/ karst processes are confined to the contact surface between carbonate rock and gypsum.

The formation of subsurface cavities is due to the leasching of a gypsum waterproof layer, by active subsurface karst water. As a result gypsum caves are formed in the river valley slopes /Syukeevo, TASSR, BASSR/ and lakes /the Vyatka river valley, Kirov region/. 4. Suphate section with thin dolomite interlayers. The presence of thin dolomite interlayers allows the water to penetrate the gypsum deposit and to dissect it. As a result of gypsum leaching cave karst cavities appear over the contact surfaces with dolomite.

5. Chalk section with clay interlayers /Ulyanovsk region/. Clay interlayers are waterproof. They produce karsting stages of small depth preventing the development of a deep and thick karst.

Climatic, geographic and landscape conditions play an important role in the development of karst. Geographic landscape zoning connected with the balance of warmth and humidity is well pronounced on vast plains. Seven landscapes and geographical zones are distinguished in the case of the Russian Plain: tundra, forest-tundra, forest, forest-steppe, steppe, semidesert, desert. In accordance with these zones we should distingusih landscape-geographical types of karst. This approach is quite justified. It reflects the contemporary principles of physical-geographical zoning of the USSR territory /1968/. Thus G.Chabot distingusihed /Gvozdetzki, 1954, p. 331/ in accordance with the climatic-landscape principle "Mediterranean" karst temperate climate karst, torpical karst, humid subtropical karst and desert karst. The latter type /both plain and mountain/ is common in the Soviet Central Asia. Humid subtropical karst is well represented in Georgia /Black Sea area/. The climatic-landscape type of karst peculiar to the USSR is the one common in the "ever frost" area in Eastern Siberia /Paramuzin, 1953, Gvozdetzki, 1954/. C.Kossak /1952/ adheres to the same principle of classification as Chabot. The intensity of karst processes depend on climate humidity, the best conditions for the development of karst being, according to G.Kossak, in the typical Mediterranean areas.

Climate-landscape vertical zoning is absent from plains. However, even insignificant elevations create, because of greater humidity, better conditions for the formation of surface run-off and, indirectly, for the development of karst processes.

In the geological composition of the sedimentary cover, thanks to the calm tectonic territory development, the "levels" of old karst with old an buried crusts of weathering and with the forms of old buried karst /paleokarst, Stupishin, 1967/ are preserved. The old karst levels reflect the long-term continental stages of territory development. Continental gaps in the Paleozoic Volga-Ural anteclise are established in the pre-Famonnian, pre-Visean and, partly, Upper Permian, pre-Upper Jurassie periods and, with scouring, in the Neogene and Quaternary periods /Stupishin, Otreshko, 1967/. In view of the carbonate collector problem the knowledge of karst in the Paleosoic sections is beoming increasingly important and has already become an important subject of investigation on the part of oil, gas and other mineral resources prospectors.

Lower Mesozoic karst occurs in the Middle Volga valley /the Smara Bend/. Perm carbonate rock is characterised by extremely old karsting. Old karst zones with an overall thickness of 40 m are distinguished. The working out of karsting zones took place under the conditions of slow tectonic rising of territory during Triassic and lower Jurassic and the corresponding lowering of underground water level. Surface and subsurface forms of old karst have been studied. Karst fields of 4 km^2 with a depth of downcutting of up to 50 m, are notaworthy. Subsurface karst cavities-tunnels located 70 m below the surface are observed. They are filled with blueish-green clay containing tree-trunk gragments and pyrite druses. Humid and warm climate in lower Mesozoic period resulting in the growing of old coniferous and tree-like ferns is established by the geomorphlogical and paleobotanical method. In the crust of weathering of lower Mesozoic karst rock with high alumina content is formed /zhigulites/.

Karst is particularly wide-spread due to Alpine Orogenesis. Three big phases of neotectonic movements are characteristic of the east of the Russian Platform /Nikolayev, 1962/. As a result of neotectonic movements deep valleys of neogene scourings were downcut into the thick layer of Paleozoic soluable rock. Then they were filled with a thick layer of sand and clay formation of the akchagyl stage /Pliocene/. Terraced accumulation-erosion were worked out o in the Quaternary period. The formation of neogene-Quaternary karst is an important geological phase which created the basic features of the modern development of plain karst confined to river valleys.

The economic utilization of plain karst areas presents a very intersting problem. Karst subsurface waters characterised by a constant and voluminous discharge /over 200e/ /sec/ are successfully used for water supply of many cities and towns /Kazan, Arzamas and others/. Iubular springs coming to the surface from the deep levels of jointy carbonate--sulphate rock of the Permian system /Izhminvod, Sergievskminvod and Bakirovo spas/ possess balneological properties. Valuable building materials are to be found in karst areas and large quarries are situated there /Middle Volga region/. Oil and gas deposits are contained in karst carbonate rock of carboniferous age.

The well-known bauxite deposits in the north-west of the Russian plain are associated with the old karst cavities of Lower Paleozoic /Silurian period/. Large and numerous solution lakes are of fishing industry and as tourist attractions. Karst cavities are the sites for artificial reservoirs and are used for sports. Karst phenomena are criteria in prospecting for various raw and construction materials. Karst also has a number of negative features which must to taken into account during construction work. Observations carried out in cave laboratories are of great theoretical and practical interest.

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THE EFFECT OF "TERRA ROSSA " TYPE SEDIMENTS ON DOLINA MORPHOGENESIS

According to the investigation results of the last years it became obvious that the soils, humic sediments and permeable non-karstic rocks covering the surface of the karstic rocks play an important role in the karstic solution processes. The fact was also proved that under the bauxite sediments the formation of karst phenomena is also possible /investigations of Papastamatiou, Bushinski, Combes and others/. Under the terra rossa type sediments covering the karstic surface in a wide area the conditions are more favourable for the karstic solution processes.

In the course of my investigations the effect of the terra rossa type sediments, first of all of the Aggtelek karst, on the dolina morphogenesis was searched L. Jakucs and others related previously to the fact that connection may be presumed between the morphology of the dolina and the quality of the clayey sediments filling it.

The terra calçis type sediments of the Aggtelek karst are fossil relics and reactivated soil formations, respectively. The most important features of them were investigated from the point of view of the karstic processes and the conclusion was drawn that during the development of the dolinas the terra rossa filling them are significant factors.

On the basis of the micromineralogical investigation of the dolina sediments of the Aggtelek karst the following results were established: According to the mineralogical genesis the terra rossa sediments are the redeposited substances of three rocks at least /certain part of them was redeposited several times/:

1. Minerals originating from metamorphic rocks: garnet with inclusions, kyanite, turmaline, epidote, clinozoisite, zoisite, anthophyllite, tremolite, amphibole of yellowish-green pleochroism; quartz of undulatory extinction; and partly the feldspars.

2. Minerals originating from igneous /presumably granitic/ rocks: ilmenite, titanite, biotite, chlorite, apatite, xenomorphic quartz with inclusions, partly the feldspars and partly the muscovite.

3. Minerals originating from volcanic rocks: magnetite, non-rounded zirkon, augite, partly the biotite, the idiomorphic quartz, the intact feldspars, and the volcanic detritus.

The crystalline and rounded varieties of certain minerals relate to two kinds of rocks; a younger and an older generation can be distinguished.

According to the DTA and X-ray investigations of the clay minerals of the terra rossa sediments the illite is of predominant role but small quantity of kaolinite and gibbsite also occurs.

Investigating the chemical composition of the substances the following results were obtained: SiO_2 = 42 to 66 per cent; Al_2O_3 = 16 to 42 per cent; Fe_3O_4 = 1,9 to 5,9 per cent; Fe_2O_3 = 6 to 16 per cent; MnO = 0,15 to 2,2 per cent.

The quantitative change of the humus content relates to the fact that the clays accumulated in the dolina were previously the soils of the slopes of the dolina. The humus content change between 0,733 and 2,849 per cent. Very high values /3,899 to 4,001 per cent/ were given by the terra rossa samples which, on the basis of their appearance, may be considered as the relics of the terra rossa rendzinas deposited in the dolina, and which were described by P. Stefanovits. These form in the dolina independent dark-coloured layers of several metres thickness. In other cases these formations were deposited in the dolina mixed with real terra rossa sediments of smaller humus content.

The pH-value of these sediments changed between 5,3 and 6,6. The potential acidity measured by KCl solvent showed different values between 4,2 and 5,7.

Having investigated the mechanical composition of the terra rossa sediments we stated that the quantity of the clay fraction may reach 72 per cent and within this value the fine clay fraction may reach the value of 50 to 57 per cent of the total value. The silt fraction changes between 15 and 25 per cent and the quantity of psammites remained always below 10 per cent.

Previously the presence of the terra rossa sediments covering the karst surface was explained by the phenomenon that this sediments consisting mainly of fine-grained and compact clay minerals exclude the underlying carbonaceous surfaces from the solution processes, because due to their impermeability they hinder the infiltration. The investigations made by perkolograph showed that the impermeability of the terra rossa type sediments depends on the grain size composition of the layer, on the quantity of the clay fraction, on the layer's thickness, position, organic substance content, further on the richness of the edaphic assemblage and presence of it, respectively.

Part of the terra rossa type sediments proved to be practically impermeable, in other part of them the infiltration became constant in a low level but only after certain space of time. The third part showed relatively good permeability.

Difference had to be made between the two kinds of appearance of the terra rossa type sediments:

1. The type, rich in edaphic assemblages and intergrown with roots and which is of relatively high humus content and of more loose sturcture showing recent soil features, is permeable for water and capillar

network can be found in it. The slopes of the dolina are covered for the most part by terra rossa type sediments of this type. The separating ridges between the dolinas and the upper layer of the dolina floor filled with clay /1 to 1,5 m thick/ as well as the slopes of the dolinas are covered by this type of terra rossa sediments. This is called in the following Type A.

2. Only the upper part of the terra rossa accumulations of thickness /2,5 to 25 metres/ is of soil structure. In the lower part the clay is poor in humus, and in the grain size composition the ratio of the clay-, and colloidal fractions is increased. In the overwhelming majority of the cases this type of terra rossa is of impermeable behaviour /Type B/.

According to our investigations the terra rossa of Type A is permeable for rainwater and the sediment is relatively permeable. During the infiltration the lime aggressivity of the water considerably increases. This phenomenon can be explained first of all by the fact that the terra rossa of Type A is densely intergrown with roots. In the course of the roote respiration these produce CO_2 and the CO_2-content of the air of the soil caves is multiplied comparing it with that of the fresh air. In addition to the CO_2-production of the roots considerable significance is attributed to the CO_2-production of the biosphere of the soil, first of all to the microorganism. According to all probabilities the CO_2-quanttity originating in the course of the functions of life of the monoplastids and microbes forms considerable part of the CO_2-quantity being in the soil and in its air. As to our hypothesis CO_2 may originate during the decomposition and transformation of the organic substance of the terra rossa layers being rich in organic substance and humus is greater than that of the layers being poor in organic substance. The more detailed investigation of this phenomenon is in progress but it can be stated that the higher CO_2-content, which is significant from the point of view of the karstic solution, could be registered, as well.

The structure of the terra rossa of Type A, rich in humus and roots, is more loose than that of the Type B, and this fact explains at the same time the relative permeability of the first type.

On the complex effect of these the lime-solving capacity of the water infiltrating the terra rossa of Type A is much greater than that of the water of rainwater. Therefore it can be stated that this type of terra rossa intensifies the solution processes of the underlying limestone so that it highly surpasses the measure of solution of the free limestone surfaces.

The accumulation of the terra rossa of Type B may be considered impermeable. Its structure is very compact, roots and higher humus content can be found only in the uppermost layers. It was observed that in the strata of the thicker dolina sediments the organic substance content decreases downwards and below 2 metres its quantity varies only between 0,7 and 1,2 per cent. The rainwater, either becoming aggressive in the upper zone binding the CO_2, cannot infiltrate the thick filling up, leastways in considerable quantity concerning the solution.

In several cases of our investigations the lowermost part of the thick layers was moist. In these cases, however, the water got the terra rossa by lateral infiltration above the limestone floor.

It can be stated, therefore, that the terra rossa accumulations of Type B surpassing the critical thickness of 1,5 to 2 metres exclude more or less the underlying limestone surfaces from the solution processes and contrary to the thin terra rossa accumulations of Type A they hinder the karst formation of the underlying rocks.

The opposing effect of two kinds of the dolina sediments mentioned above /according to the qualitative and quantitative appearance of the terra rossa/ on the karstic solution processes of the limestone surface is of important conclusions.

In the areas investigated the major part of the dolinas developed as sumps. The originally cone-shaped depression of steep slopes came into existence in such a way, partly by means of capture. Further they became the mesh of the terra rossa cover and of the terra rossa type sediments carried by rainwaters.

The terra rossa dolina sediments could display their effect in the way mentioned above.

1. The terra rossa sediments of Type A accumulated in the bottom of the dolina in thin layer either intensify the solution processes of the dolina floor or maintain the former rate of deepening. The most rapid solution may take place in the place of the leakage of

considerable water quantity, in the deepest point of the dolina, so that the reversed cone, resp. cone-frustrum type shape of the dolina remains until the accumulation of the terra rossa carried by water surpasses the critical thickness of 1,5 to 2,5 metres, and becoming impermeable it decreases the solution processes in the deepest points of the dolina.

A part of the terra rossa got the dolina is washed into the fissure and solution cave system of the limestone because the clay forms colloidal solution with water and can be easily transported. The finest clay fraction /the quantity of which is frequently more than 50 per cent/ gets the deeper parts of the karst /it can be found also in the roofs of the caves in a depth of 80 to 100 metres from the surface/ and it is deposited only in the most narrow fissures.

In the case when only terra rossa sediments of relatively small quantity get the dolina from the sediment-collecting area and certain part of this gets the fissure system; the thickness of the sediment in the dolina-floor reaches the critical measure either during a long time or by no means. In this case the deepening of the dolina continues <u>vertically</u> and the original <u>cone-shaped form</u> which is ever growing, is preserved. The downward deepening of the deepest point is promoted by the terra rossa of Type A lying on the bottom, and in such a way by the lapse of a reasonable time a dolina of large-sized filler cross section develops. Such precedents of the dolina evolution can be seen on the surface of the Nagyoldal of the Aggtelek Karst and in numerous other places.

In those cases the slopes are covered by thin clay layer, the transportation is slow, the catchment basins are relatively small, the dolinas are vertically developed and the cone-shape remained constant up to the present. According to the bore-holes the terra rossa sediment of the dolinas do not surpass the thickness of 1,5 to 2,5 metres in general, they are decidedly terra rossa sediments of Type A, and are rich in humus /dolina form No. 1./.

2. When the accumulation of the terra rossa sediments reaches the critical thickness the morphological development shows another way. The clay accumulated in greater quantities becomes Type B and due to its partial or total impermeability the water infiltration weakens at the deepest points of the dolina. The rainwater infiltrates further the contact with the compact limestone and in the narrowing edge of the dolina sediment where it does not surpass the critical thickness mentioned above. The stronly corroding water which gets across the thin terra rossa contacts the limestone at the edge of the dolina and not at the deepest point of it. The fissures of the limestone are enlarged and dissolved by this water. This leakage form may be called <u>lateral leakage</u>. The water acts mainly on the place of infiltration hence the deepening as well as the solving devastation are here the strongest. Certain part of the water disappears in the fissure system and certain part of it, however, goes forward under the overlying clayey strata towards the deepest point of the dolina floor, but its corrosion capacity is decreased because it reached the saturated stage. This water only <u>uses</u> the fissures system formed previously in the bottom of the dolina, but is it unable to widen the fissures, moreover it promotes the clogging ot them. In the course of its way it drenches

the lowermost strata of the dolina, as it was stated in numerous cases. After a longer space of time the laterally leaking water weakens and corrodes the limestone in such an extent that, with gradual break down, the deeper bottom surface of the dolina widens. In function of the progression of this process and of the deposition of further terra rossa sediments the zone of intense corrosion moves laterally outwards. The relative flattening and levelling of the dolina floor may be called the planation of the dolina bottom.

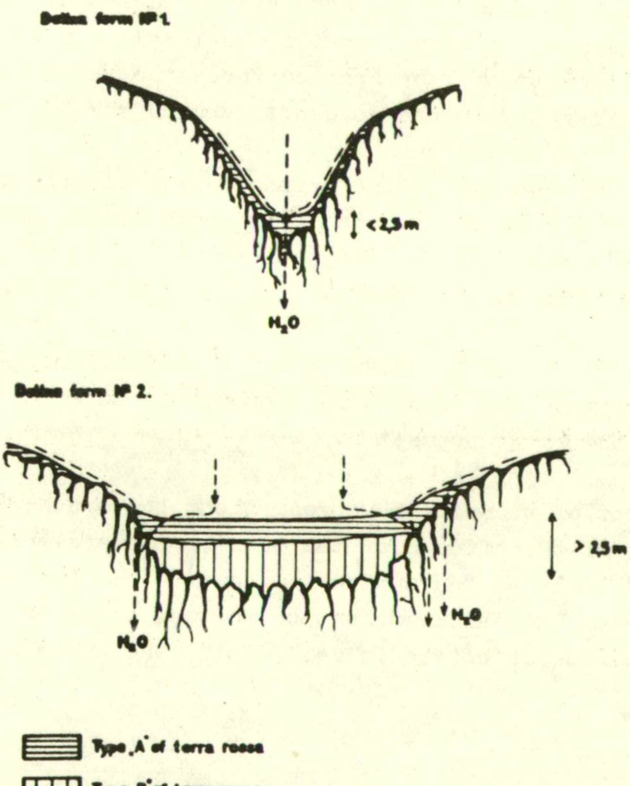
By the lapse of a reasonable time this evolution form becomes predominant in the dolinas of thick sediment mass and the original cone-shape of the dolina transforms into a wide bowl-shaped form. The dolinas of the southeastern part of the Aggtelek Karst represent this morphological type. The thickness of the terra rossa sediments in them is between 5 to 20 metres, except the marginal parts. Their sediment-collecting area is relatively large and the transportation of the sediments is rapid. The deeper zones of the dolina sediments consist of terra rossa sediment of Type B.

The sections of the filling strata relate to the lateral post-deepening. These strata are curved, they wedge and are sometimes interrupted and change in quality according to the fact that what part of the accumulation is the deposition place of the fresh terra rossa sediments. In case of deepening of other kind the filling strata ought to continue towards the margin of the sediment. The bowl-like appearance is further called dolina form No. 2.

As a result of the lateral evolution the lower part of the dolina cuts back more rapidly than its middle part, therefore the slopes are frequently slightly bulging. The process of bulging of the dolina sides reacts upon the devastation of the terra rossa cover of the dolina sides, i.e. on the bulging surfaces this process become accelerated and the limestone becomes barren and on this surface the karr-formation prevails.

In the course of the widening process the dolinas elogante in the indicated directions. Between the dolinas approaching each other first of all in the direction of the common lithoclases the separating ridges become lower and break down so that several dolinas may merge into one another. The relics of the ridges between them can be always found. When the clayey filling of the dolina begins to spread over the separating ridge, its corrosion accelerates for a short time until the overlying layer reaches the thickness of 1,5 to 2 metres. Due to the greater thickness of the overlying sediment the relics of the ridge preserves and it can be found at a later phase, too, on the uvala bottom surface formed in the course of merging.

In numerous places of the area investigated the phenomenon occurs that on the slopes above the present dolinas the terra rossa of Type B forms relatively thick /5 to 8 metres/ series and the former depression filled by it got vertical position comparing to the present dolina. On the basis of the fact mentioned above the explanation of this phenomenon is obvious. Where the evolution of the former karst surface formed dolinas and which were filled up by terra rossa sediments the possibility of further deepening comes to an end. In the course of the lateral widening the place of the new break downs was put over the neighbouring areas where the thin overlying stratum promoted their formation. In certain cases the over-deepening became possible comparing the level to the former bottom surface, because the newly developed dolina having smaller sediment collecting area was filled up more slowly and the sediment of the older dolinas getting vertical position was transported into the over-deepend dolina only later, due to some kind of difficulty. The surroundings of Lake Vörös and other places show excellent precedents.



Numerous measurements were done to recognize the indirect double role of the terra rossa sediments played in solving the limestones. It must be emphasized that the solution-promoting effect of the terra rossa sediments occurs when this cover replaces the soil for the most part. The chemical changes of the water-infiltrating it and forming lime-aggressive compounds are hardly known. According to our measurements while the CO_2-content of teh air of the uppermost 30 centimetres of the terra rossa soil is only 0,1 to 0,5 per cent now in a depth of one metre this reaches 1 per cent. On the basis of this it may be presumed that the carbonic acid content of the infiltrating water increases down to a certain depth and its aggressivity is greater at those places where the soil is of 0,5 to 1 metre thickness but is permeable /on the overwhelming majority of the karst surfaces the thickness of the terra rossa sediments does not surpass the 30 to 40 cm/.

Differences are in the carbonic acid content of the soil-air according to the quality of vegetation, too. The terra rossa sediments covered by forests showed higher carbonic acid content, in general.

The effect of the terra rossa accumulations being not soil but thicker rock strata proved to be a fact dwarfing the karst formation.

A lot of transitions appear among the opposing effects and, what of the effects of the terra rossa sediments will prevail depends on the manifestation of other factors. For instance the thickness can be neither determined exactly which could be authentic in determining the prevalence of on or another of the effects /positive or negative/ of the terra rossa sediment.

The effect of the terra rossa sediments in only one factor in the morphological evolution process of the dolinas. This effect may be promoted or hindered in closest complexity by other factors /petrographical, tectonic, pedological, hydrological, biological, geomorphological, phylogenetic, etc./. Therefore it is not to be expected that all the dolinas covered by terra rossa sediments can be assigned exactly to one of the morphological types described above. The development either prevails variably /in negative and positive forms/ in the course of its movement processes or the effect of the terra rossa sediments does not prevail and its role as evolution factor can be determined only in the given period and comparing with the effects of the other factors.

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Edited by Prof. Dr. László Jakucs, Director of the
Department of Physical Geography
Szeged, Táncsics M. u. 2. Hungary

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